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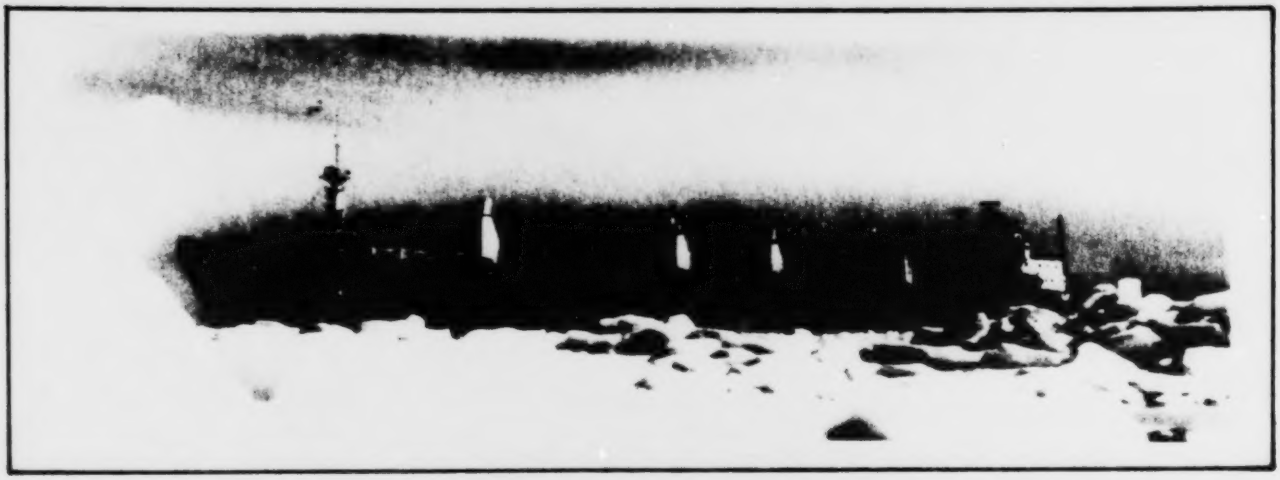

M.V. Arctic Scientific Program

1979-1981 Performance Review

Prepared for

Transportation Development Centre

Montréal

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MV. ARCTIC SCIENTIFIC PROGRAM

1979 - 1981 PERFORMANCE REVIEW

Prepared for
Transportation Development Centre
Montreal

Prepared by
T.H. Peirce
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July 1985

305193

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DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the official views or policies of the Transportation Development Centre.

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17. Abstract

This report provides an overall review of the M.V. Arctic Scientific Program from its inception in January 1977 to completion of data analysis in April 1985. The report describes the program and its objectives, the instrumentation system fitted on the ship, the arctic route conditions and the data collection activity. The report then summarises the main findings of data analysis with respect to the following three components of ship performance evaluation in ice:

- Ice Transiting Performance,
- Propulsive Performance and
- Structural Performance.

As an overall conclusion, the results show that, largely due to an above-minimum propulsive power level, the M.V. Arctic has ice transiting capabilities in excess of those normally expected of her ice class, but needs these capabilities for her commercial arctic missions. Analysis of structural performance reveals a risk that design strength may be exceeded under ramming mode conditions. The report concludes with a focus for future research based on the program findings.

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R. Bertrand

17. **Résumé**

Ce rapport passe en revue le Programme d'évaluation scientifique de l'Arctic, depuis le début en 1977 jusqu'à l'achèvement de la phase "analyse des données" en 1985. Il décrit le programme lui-même ainsi que les objectifs poursuivis, le système d'acquisition des données dont l'Arctic a été pourvu, les conditions de navigation dans l'océan Arctique et les activités de saisie des données. De plus, il récapitule les principales conclusions issues de l'analyse des données recueillies et concernant les trois aspects suivants:

- Qualités évolutives dans les glaces,
- Comportement du groupe propulseur, et
- Tenue de la coque aux charges des glaces.

Une conclusion générale s'impose: grâce surtout à une puissance installée dépassant les normes minimales, l'Arctic a manifesté des qualités évolutives supérieures à ce que l'on attend d'un navire ayant cette cote arctique, qualités cependant indispensables au vu des conditions de navigation rencontrées lors des périples commerciaux dans l'Arctique. Côté comportement structural, l'analyse des données fait craindre la possibilité d'un dépassement de la résistance nominale de la coque, à l'occasion notamment des marches alternées où l'Arctic doit charger les glaces pour se fraver un passage. En dernière partie, le rapport indique l'orientation à donner aux recherches à venir, à la lumière des résultats acquis jusqu'ici.

18. **Mots-clés**
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SECTION 1

INTRODUCTION

This report provides a review of the MV. Arctic Scientific Program and summarises the main results obtained from the 1979-1981 data acquisition period.

The review commences with a brief history and description of the seven year scientific program from its inception in January 1977 and covers the three main program phases of: ship instrumentation; data acquisition; and data analysis which was completed in March 1985. The report then addresses the following specific subjects.

- Route and ice description examines the seasonal variations in the ice regime with the interrelated effects on the ship's arctic routing, mode of operating and voyage-time leading to the possibility of shipping season extension in favourable years.

- Ice-transiting performance examines the capabilities of the MV. Arctic with respect to the continuous, ramming and manoeuvering modes of progression through ice, and demonstrates that the ship has a capability in excess of that normally expected of an Ice Class 2 vessel.

- Propulsive performance examines the extent and effect of ice ingestion on the ship's propulsion system and, with only minor qualifications, confirms its reliability and effectiveness in ice-related operations.

- Structural performance examines the effect of ice interaction with the ship's hull in the various operating modes with particular emphasis on the extent of ice impact, load and pressure activity and the consequent effect on structural design criteria.

- Instrumentation system examines the effectiveness of the data acquisition system installed on the MV. Arctic, its strengths and weaknesses with respect to the original program objectives and the results of the operational experience, all of which provide valuable guidelines for future instrumentation systems.

Each of the above subjects is contained in a separate section of this report, the substance of which has been drawn from the final reports of the data analysis contractors as provided in Attachment 1.1. Each section is complete in itself and contains an appropriate summary of principal findings.

The final section of this report uses the above findings to develop and set down matters for the further focus of scientific research into arctic shipping operations.

ATTACHMENT 1.1

MV. ARCTIC SCIENTIFIC PROGRAM

1979 - 1981 Final Reports
prepared for
Transportation Development Centre

TP.5170	MV. Arctic - Ice-transiting Performance (continuous-mode) by Albery, Pullerits, Dickson and Assoc., May 1984.
TP.5320	MV. Arctic - Ice-transiting Performance (ramming-mode) by Arctec Canada Ltd., October 1984.
TP.5684	MV. Arctic - Manoeuvering Performance by German & Milne Inc., September 1984.
TP.5167	MV. Arctic - Propulsive Performance by Melville Shipping Ltd., March 1984.
TP.5680	MV. Arctic - Structural Performance by Arctec Canada Ltd., March 1985.

SECTION 2

MV. ARCTIC SCIENTIFIC PROGRAM BACKGROUND

2.1 Program Objectives

The development of reliable technology and sound operational practices for arctic shipping is fundamental to the safe and economic exploitation of oil and mineral resources in the Canadian Arctic. In furtherance of these aims and recognising the special difficulties and risks surrounding arctic marine operations, the Government of Canada has taken the following two important steps in recent years.

- In 1972, proclaimed the Canadian Arctic Waters Pollution Prevention Act (CAWPPA) supported by the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) to provide standards, criteria and guidelines for the admission of ships to the Arctic based upon the best knowledge available at that time.

- In 1975, agreed to participate jointly with a group of Canadian shipowners in the construction and operation of the MV. Arctic, a CASPPR Class II icebreaking cargo vessel shown in Attachment 2.1. Management of the MV. Arctic is conducted through a joint company, Canarctic Shipping Ltd., and the various relationships are shown in Attachment 2.2. The vessel is leased from Royal Trust by Canarctic who operate the vessel in the arctic shipping seasons (July to November) and charter her to North Water Navigation for the remainder of the year.

Federal responsibility for the above is vested with the Ministry of Transport. In the latter case, a condition of government participation was that the technical and commercial experience derived from the MV. Arctic venture would be made available to all sectors of the Canadian marine industry having shipping interests connected with arctic transportation. To that end, the Ministry of Transport assigned the responsibility for recording and publicizing the technical components of this project to the

Transportation Development Centre through a Memorandum of Understanding signed by CMTA and TDC, in September 1976. TDC initiated this seven year research program of instrumentation system development, data collection and preformance analysis which followed Treasury Board approval in January 1977. The program has the following six objectives.

OBJECTIVES

1. To evaluate the structural strength standards and other design criteria assumed to be necessary in the Arctic Shipping Pollution Prevention Regulations, for a vessel of Class II, and to offer a quantitative and qualitative appraisal of these standards for other Classes of icebreaking cargo vessels envisaged by these Regulations.

2. To evaluate the restraints on seasonal operation periods and zones currently established in the regulations for a vessel of Arctic Class II.

3. To develop improved or more appropriate forms of navigation and communications equipment for Arctic Class vessels with particular respect to ice reconnaissance and forecasting; position finding devices and collision avoidance systems.

4. To establish a co-relation between the performance of the tank-tested model of the vessel in ice with actual vessel under Arctic operational conditions, and to establish its icebreaking efficiency under actual and diverse operational conditions of weather and ice intensity.

5. To establish the degree of effectiveness, in the continuous icebreaking mode, of special features incorporated into the initial design of the proposed vessel such as an air bubbling system to reduce the friction effects of broken ice and a ducted propeller feature.

6. To provide an instructional base upon which the expertise of ice navigation and commercial ship operation in Arctic waters may be further developed and dispensed.

It is immediately evident from the above that there are three important and interrelated thrusts embodied in these objectives, namely, the evaluation and improvement of the design, performance, and safe operation of icebreaking ships. Actual field experience is the only reliable basis for evaluating the soundness of current codes of arctic marine practice and the MV. Arctic Scientific Program was designed and implemented with these essential purposes in mind.

2.2 Program Implementation

The plan of implementation of the MV. Arctic Scientific Program consisted of three main phases as follows:

Phase 1 - Provision of instrumentation aboard the vessel to sense and record the requisite scientific data.

Phase 2 - The collection and annual reporting of scientific data whilst the vessel was engaged in commercial arctic voyages.

Phase 3 - Detailed analysis of the collected data to gain a quantitative measure of the vessel's performance in ice, leading to the development and trial of more advanced instrumentation systems.

The description of these three phases of the program is as follows:

Phase 1. The contract for this phase was placed in 1977 and was completed with the commissioning of the instrumentation system in June 1979. The design and installation was completed by mid 1978 when the ship was delivered and followed immediately by structural load calibration. The first arctic season, July to November 1978, was used for familiarisation and debugging the system. All calibration and acceptance tests were completed in June 1979. The main events of Phase 1 are provided in Table 2.1.

Table 2.1

PHASE 1 Events	Contractors	Description
Design & Instal System 1977-June 1978	German & Milne Fenco	256 Channel computerised sensor system with 169 sensors allocated to structural strains on finite element array
Structural Load Calibration July 1978	German & Milne Fenco	Strain gauge calibration based on 50 ton load applications to structure
Familiarization Period 1978 Arctic Season	German & Milne	General running and debugging of system during arctic voyaging
System Calibration & Acceptance Tests April-June 1979	German & Milne	Final calibration of the system and development of conversion equations

Phase 2. The instrumentation system has been operated by a number of contractors over three full arctic seasons from July to November for the years 1979, 1980, and 1981 and has accumulated ship operating data on a total of twelve round voyages between Europe and the arctic loading terminal at Nanisivik in Strathcona Sound. Ship performance has been monitored as deemed necessary throughout the ice-transiting period and at other times to give comparative open-water data.

In addition to the above original program, full advanatage has also been taken of other opportunities to conduct four sets of dedicated trials. The purpose of these trials was to examine special hull-ice interrelationships under controlled conditions in uniform and non-uniform ice regimes. Reports on these activities have been published and distributed to interested parties. The principal events covered in Phase 2 are described in chronological order in Table 2.2.

Table 2.2

PHASE 2 Events	Contractors	Description
1st Arctic Voyage Monitoring Season July-Nov. 1979	German & Milne	4 round voyages - Europe to Nanisivik
Saguenay River Trials* January 1980	German & Milne	Straight-line runs & manoeuvering trails in level ice conditions
2nd Arctic Voyage Monitoring Season July-Nov. 1980	Fenco German & Milne	3 round voyages - Europe to Nanisivik
Baffin Island Trials* October 1980	Fenco/ German & Milne Lloyd's Register	Ship performance trials Hull vibration trials
Lake Melville Trials* February 1981	Melville Shipping Fenco, NRC	Exploratory commercial service probe
Admiralty Inlet Trials* July 1981	Fenco Melville Shipping	Icetransiting and ridge penetration trials
3rd Arctic Voyage Monitoring Season Part 1 July-Sept. 81 Part 2 Sept-Nov. 81	 Fenco/MSL Arctec Canada Ltd.	Europe to Nanisivik 2½ round voyages 2½ round voyages

*Dedicated Trial Periods, extra to original program.

Phase 3. This phase of the program commenced in 1982 with the preparation of a Master Plan shown in Attachment 2.3 which identifies five major projects for detailed data analysis and a program overview. The plan commenced with the preparation of a Master Data Package which described and summarized all the data collected during the acquisition phase. This package together with a complete inventory of datatapes, videotapes, and reports was a necessary pre-requisite to the detailed data analysis activities which form the objective of the third phase.

Five detailed data analysis projects were then contracted out as shown in Table 2.3.

Table 2.3

PHASE 3 Projects	OBJECTIVES	Contractor
Icebreaking Performance (continuous mode)	To develop ice, speed, power and resistance equations for continuous mode icebreaking in level ice and broken channels	Albery, Pullerits, Dickson & Assoc.
Icebreaking Performance (ramming mode)	To establish the ramming mode and ridge penetration capabilities of the M.V. Arctic and identify the optimum ramming tactics	Arctec Canada Ltd.
Manoeuvering Performance	To determine turning circle, directionial stability and docking characteristics of the M.V. Arctic	German & Milne Inc.
Propulsive Performance	To determine the thrust and torque spectra resulting from ice ingestion and the effect on strength and performance criteria for the main machinery, gear train, and propellers	Melville Shipping Ltd.
Structural Performance	To examine hull-ice structural inter-relationships under various ice-transiting conditions with particular reference to ice loadings and pressure distributions and to correspondence with structural strength design criteria	Arctec Canada Ltd.

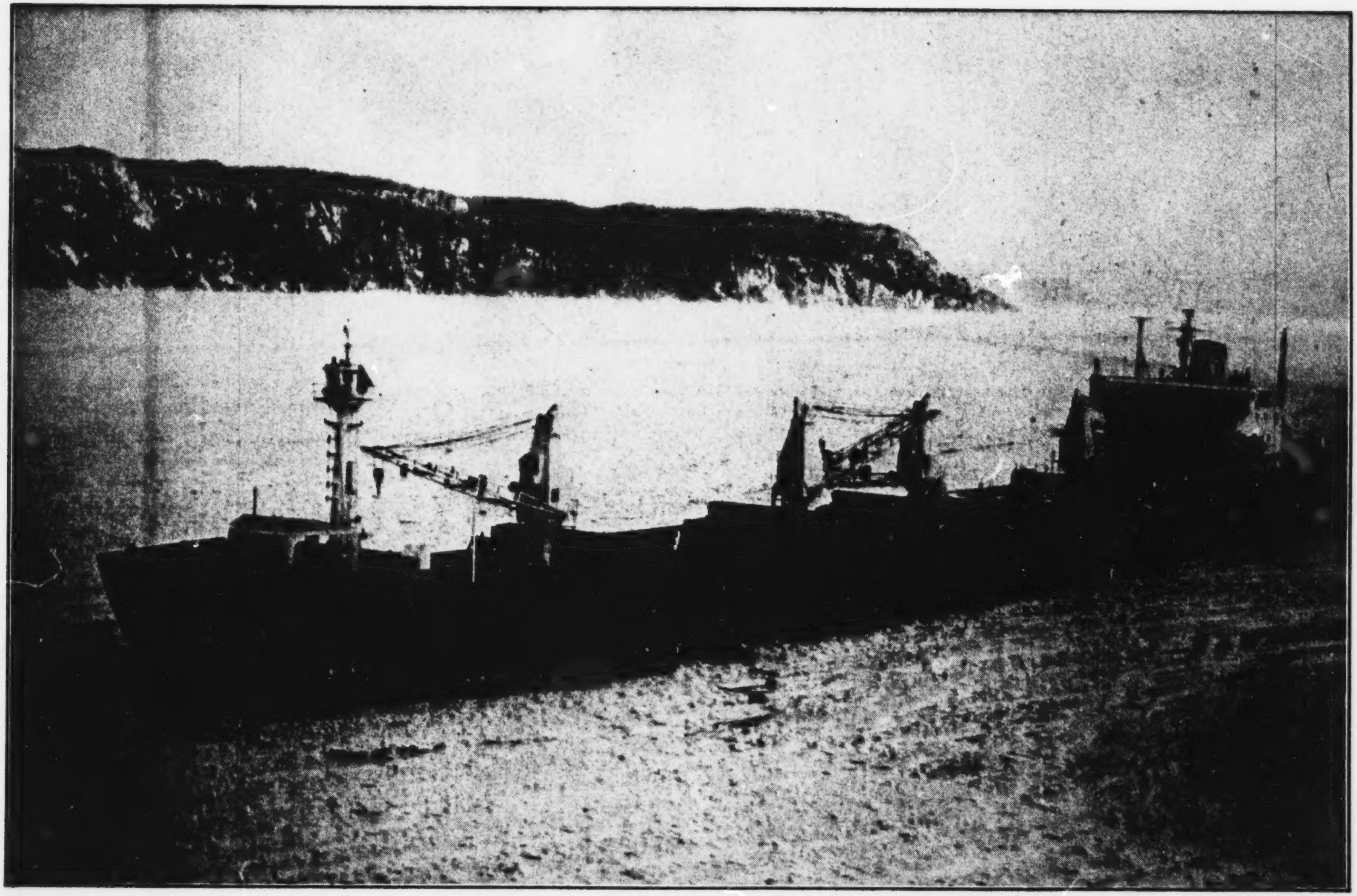
Phase 3 was completed in March 1985 with the preparation of this Summary Report which brings together the principal findings of the fore-going five projects with particular reference to the interests of regulators, designers, builders, and operators of arctic class vessels. The various outputs of the three phases of the program are shown in Attachment 2.4, and the contractors' final reports produced under the five projects of Phase 3 are listed in the references at the end of this report.

2.3 Summary

The MV. Arctic Scientific Program has extended over a seven year period at an expenditure of some three million dollars. This represents a substantial investment in arctic marine research and the knowledge gained represents a special level of circum-polar marine technological experience. The dissemination of that knowledge is the aim of a special seminar to be held in the summer of 1985.

ATTACHMENT 2.1
p. 1/2

M.V. Arctic



Attachment 2.1
p. 2/2

MV. ARCTIC - LEADING PARTICULARS

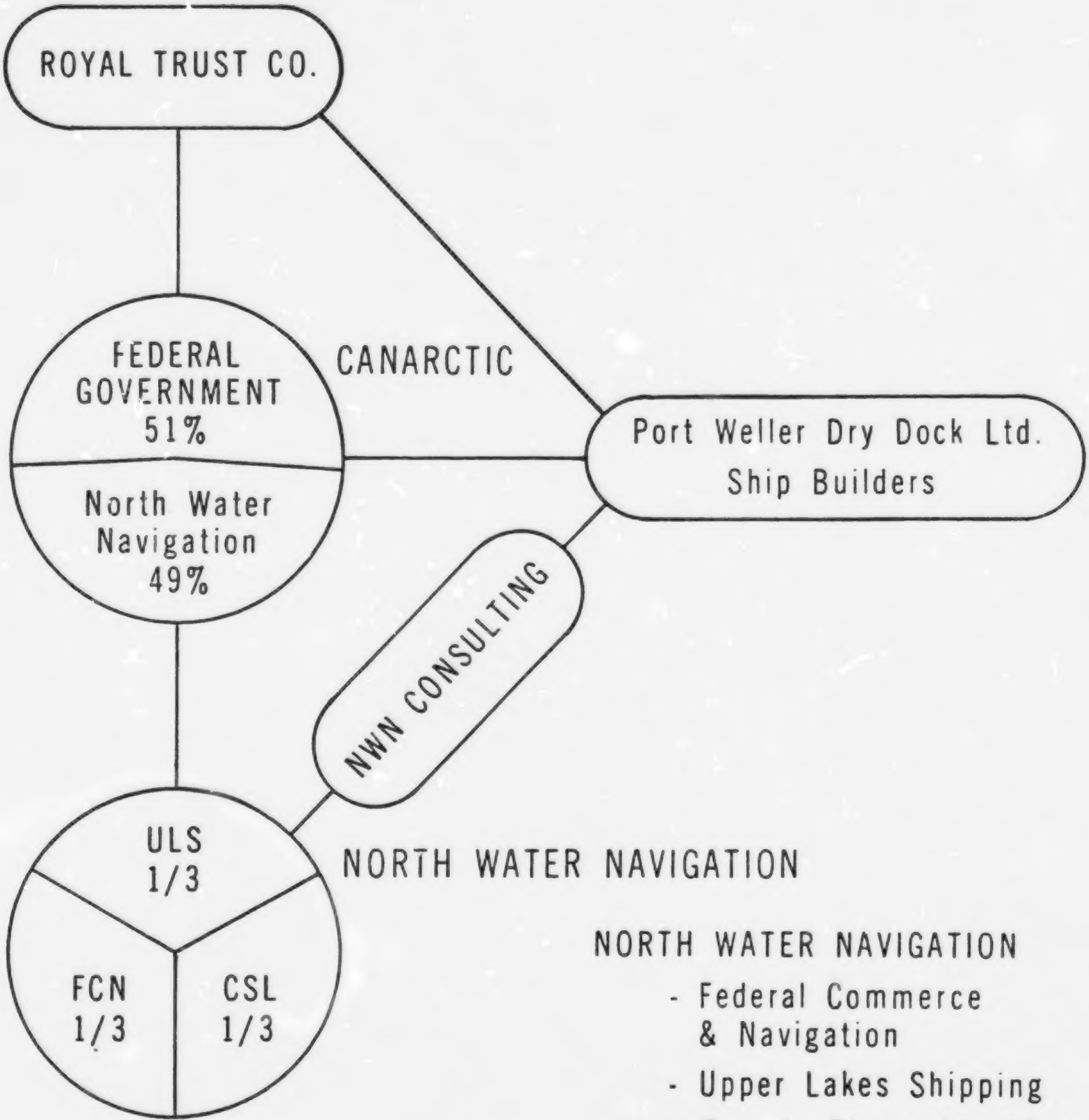
Length Overall	209.55 metres
Length Between Perpendiculars	196.60 m
Moulded Draught	22.86 m
Moulded Depth	15.24 m
Moulded Breadth	10.97 m
Summer Draught	10.82 m
Block Coefficient	0.753
Prismatic Coefficient	0.761
Light Ship	9,276.1 tonnes
Displacement at 10.82 m draught	37,724.1 t
Dead Weight at 10.82 m draught	28,448.0 t
Cargo Capacity	36,490.8 m^3
Propulsion Machinery - MAN Diesel	11,014.0 kW
Generators	900 kW x 3
Complement	40
Speed on Trials	15.5 knots
Cruising Range	14,00 Nautical miles

Designed by: Camat Ltd.

Built by: Port Weller Drydock Ltd.

ATTACHMENT 2.2

M·V· ARCTIC JOINT VENTURE



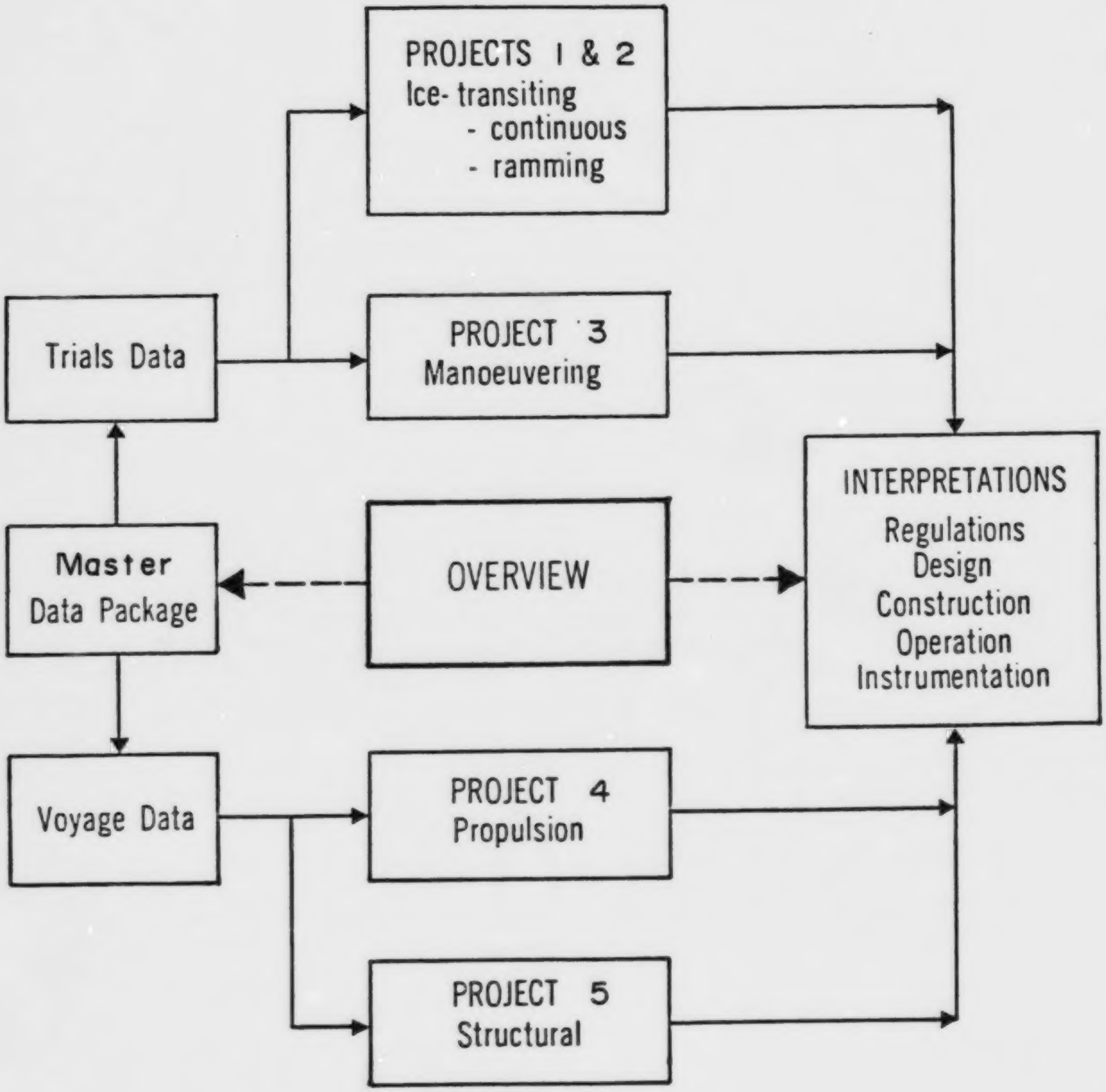
NORTH WATER NAVIGATION

- Federal Commerce & Navigation
- Upper Lakes Shipping
- Canada Steamship Lines

NWN CONSULTING

- Company for supervision of construction

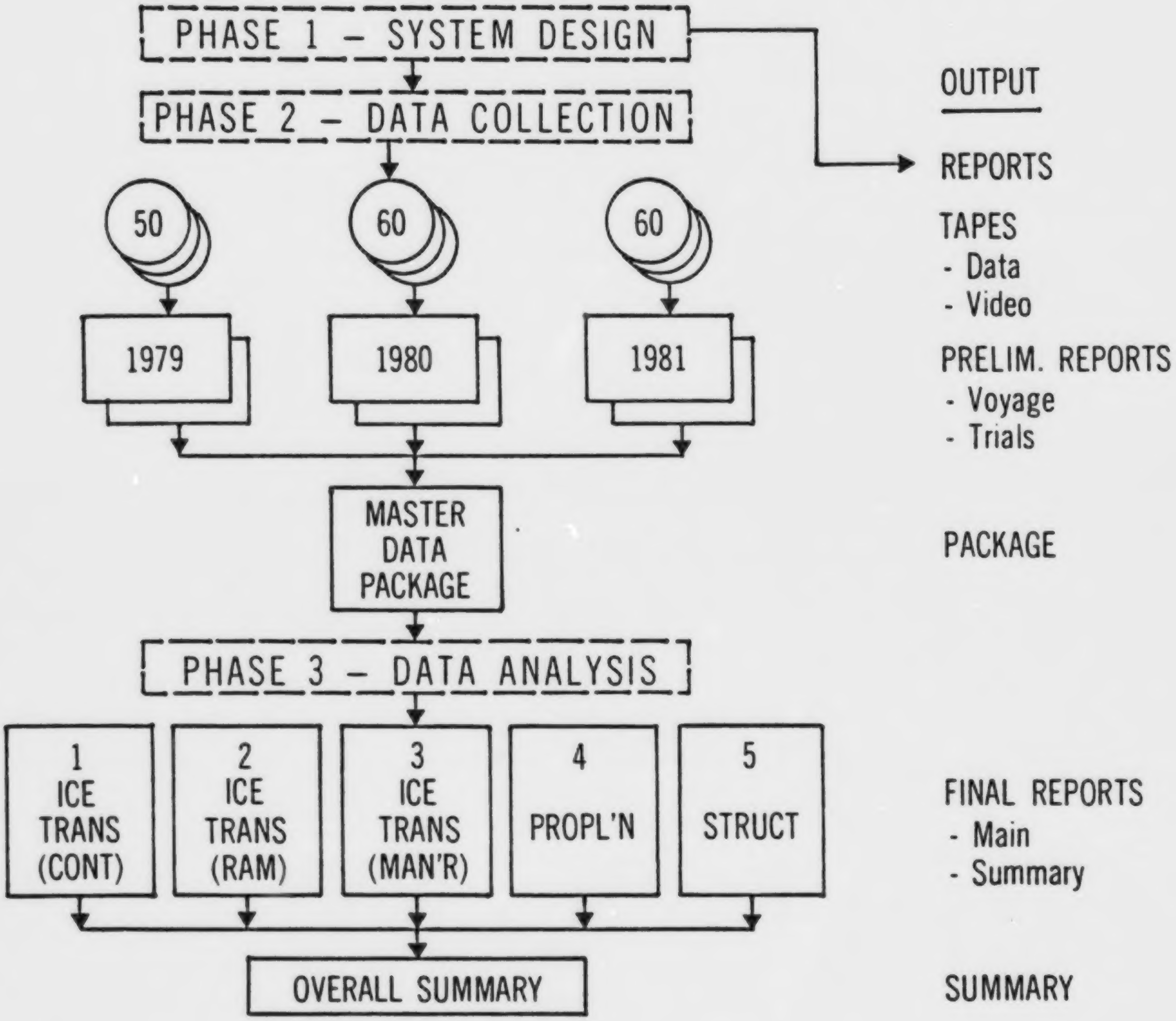
ATTACHMENT 2.3



MASTER PLAN

ATTACHMENT 2.4

M.V. ARCTIC – PROGRAM PHASES



SECTION 3

SEASONAL ROUTE AND ICE DESCRIPTION

3.1 Introduction

The MV. Arctic is an ice-class 2 vessel which operates in arctic water principally Zone 13, between June 25th and November 15th, with occasional entry into Zone 6 for a shorter shipping period. The periods are defined by the CASPPR provisions provided in Attachment 3.1. The vessel's regular shipping route is from Europe up through Davis Strait, Baffin Bay and Lancaster Sound, into Admiralty Inlet and Strathcona Sound to Nanisivik or through Barrow Strait to Resolute and Little Cornwallis Island. This section provides a description of the ice regime to be traversed and its effect on the route followed by the vessel during the shipping season with respect to both the 1979-81 program period and also the longer term potential for season extension.

3.2 Routing Considerations

During the three year arctic monitoring period, 1979-81, the vessel operated twelve commercial round voyages - from three to five voyages per season as shown in Attachment 3.2. The ship spent varying amounts of time in ice-affected waters during these arctic seasons which overall amounted to about 29% of the vessel's total seatime. The ice encountered varies greatly from voyage to voyage and from season to season and dictates the route the ship will take. Attachment 3.3 demonstrates the ship's inward routes towards Nanisivik at various times during each of the three seasons 1979 to 1981. Adjustments to the ship's route are made in accordance with the receding ice front and seasonal ice characteristics. These adjustments are made principaly to avoid major ice accumulations such as the central Baffin Pack and to take advantage of the easier ice conditions along the West Greenland coast and the North Water polynya. The extent, range and type of ice conditions which the ship encounters during these voyages not only affects her route but also determines the mode of operation, the degree of ramming needed and the assistance from icebreakers. The following overview describes the general ice regime for the region under consideration and the global effect on shipping operations.

3.3 General Ice Regime

The general ice conditions are shown in Attachment 3.4 which indicate the maximum and minimum extents of the ice front for mid-June through to late October. For comparison, the ice fronts are also shown for the monitoring years 1979 to 1981 which it will be seen, do not reach the extremes. Regional ice conditons are summarized below for the ship operating area.

3.3.1 Baffin Bay and Davis Strait

The ice regime of Davis Strait and Baffin Bay - the gateway into the Eastern Arctic - possesses important characteristics which have a major influence on navigation. The major characteristics controlling this ice regime are a relatively warm, northflowing current up the Greenland coast, which retards the fall freeze-up and enhances an earlier spring break-up of the eastern sections. Conversely, a cold, southflowing Canadian current down the Baffin coast causes an earlier fall freeze-up and a delayed spring breakup of the western sections. In addition, as a result of the currents and northerly winds, an important recurring polynya in Smith Sound at the north end of Baffin Bay called the "North Water" is evident each year. Baffin Bay is also the birth place of thousands of icebergs produced from the Greenland and Ellesmere glaciers. The icebergs follow an anti-clockwise circulation around the coastlines of Davis Strait and Baffin Bay with occasional entry into Lancaster Sound in response to the prevailing currents and winds. Icebergs represent a serious hazard to shipping operations as they are concentrated along the main shipping routes as can be seen from Attachment 3.5.

The North Water has an important influence on the spring break-up in Baffin Bay. The open water polynya, occuring early in spring, permits the development of waves which assist in the break-up of the surrounding ice. It also provides a source of heat due to the absorption of most of the solar radiation. The North Water expands southward eventually to join with open water leads forming along the Greenland coast. This forms an open water corridor into Lancaster Sound usually by mid-June. The remaining Baffin Bay icepack recedes westward througout the summer and early fall. The Bay does not always clear every year and occasionally there is also an occurance of MYR ice patches which drift into the region. Freeze-up in Baffin Bay usually begins in mid-September in the northwest sections. By October the approaches to Smith Sound, Jones Sound and Lancaster Sound are ice covered as well as bays and inlets along the Baffin coast. A rapid seaward extension of ice covers all the Bay by the end of November except for an open water lead along the coastal areas of Greenland. Ice cover can grow up to 120 cm - 150 cm in the northern sections by mid-May. Ridges and hummocks resulting from varying winter winds are prevalent features.

3.3.2 Parry Channel (Zone 13 and 6)

Summer break-up varies considerably from one year to another. Seasonal accumulation of Melt Degree Days begins about mid-June for most of Zone 13 - a little later for Resolute and Little Cornwallis Island. Summer break-up is normally complete by about the end of July in the eastern Parry Channel and is assisted by winds, the south west current in Lancaster Sound and the southward Canadian current on the Baffin coast. The ice moves southward through Davis Strait and along the Labrador coast. However, in poor summers, narrow waterways and bays will stay ice-congested as they are less effected by winds and currents and more dependent upon air temperature and solar radiation to melt the ice. Ice congestion can also be caused by winds pushing ice from one area into adjacement waterways adding sometimes unpredictable restraints on navigation. These conditions effect Admiralty Inlet.

New or young ice begins to form mid-September, the actual dates vary from year-to-year, with the beginning of the seasonal accumulation of Freezing Degree Days. The earliest formation of new ice occurs in shallow areas in bays and along shorelines. Such initial ice is very weak and easily broken up but as FDD's continue to accumulate in late September and October, it consolidates into a solid unmoving sheet over the majority of channels except for Lancaster Sound where ice is intermittent restricted motion. The ice thickness will continue to grow through the winter months until it reaches its maximum thickness occuring in mid-May. Average seasonal maximums of measured ice thickness are 150 cm - 175 cm for Lancaster Sound, Admiralty Inlet, Strathcona Sound and Pond Inlet, and 175 cm - 200 cm for Barrow Strait and Resolute. However, due to influences of winds and currents, the constantly moving ice developing in Lancaster Sound and the eastern-most sections of Barrow Strait will increase in thickness through rafting and ridging.

3.4 Route Ice Conditions and Operating Mode

It has been noted earlier that the varying ice conditions during the season dictates the ship's route, operating mode and need for icebreaker assistance. These interrelated ship operating considerations are summarised below for the early, mid and late entry periods. Ice conditions represented are those for a normal year.

Early Entry Period:

During the initial voyage in late June, early July, open pack ice and open water leads are encountered in Davis Strait, Baffin Bay and Lancaster Sound. Advantage is taken of the open water leads in the eastern sections of Baffin Bay and Davis Strait. The ship is mainly in continuous-mode until Admiralty Inlet is entered where consolidated 10/10 first year (1YR) ice is experienced of sufficient thickness (up to 1.8 m) to require ramming. Icebreaker assistance is usually called for during the initial voyage from the mouth of Admiralty Inlet to Nanisivik. On the return trip, the ship follows the previously broken channel out and thus the continuous icebreaking mode is usually possible. Frequently however, a new path will have to be rammed or broken by an icebreaker as ice movements may have filled in the channel. Once into Lancaster Sound, open water and open pack ice with some occurences of multi-year (MYR) ice floes is met. The Central Baffin Pack is receding westward leaving increasing areas of open water in Baffin Bay and Davis Strait.

Mid Entry Period:

Subsequent voyages to the Arctic - late summer and fall until mid October - are completed in virtual open water. Full routing advantage can be taken of the diminishing Central Baffin Pack. Little or no icebreaking is required, except in bad summers when ice gets clogged up in bays and narrow waterways.

Late Entry Period:

During the last voyage - late October, early November - new or thin 1YR ice, normally ranging from 0.2 m to 0.6 m, is prevalent. This permits operating in continuous-mode. MYR ice floes in loose and frozen pack, between 2 m and 4 m are frequent ice characteristics found between Baffin Bay and into Admiralty Inlet. When mixed ice conditions are encountered, the ramming-mode of operation might be required.

It is evident that the variations in ice extent, composition and severity throughout the arctic shipping season has a considerable influence on the vessel's route, operating mode and speed of advance. In order to provide an indication of the combined effect of all these factors, the diagram in Attachment 3.6 has been prepared. This diagram shows on a monthly basis, June to December, the variations in distance steamed and the time taken inwards to Nanisivik from a point of transiting the Arctic Circle.

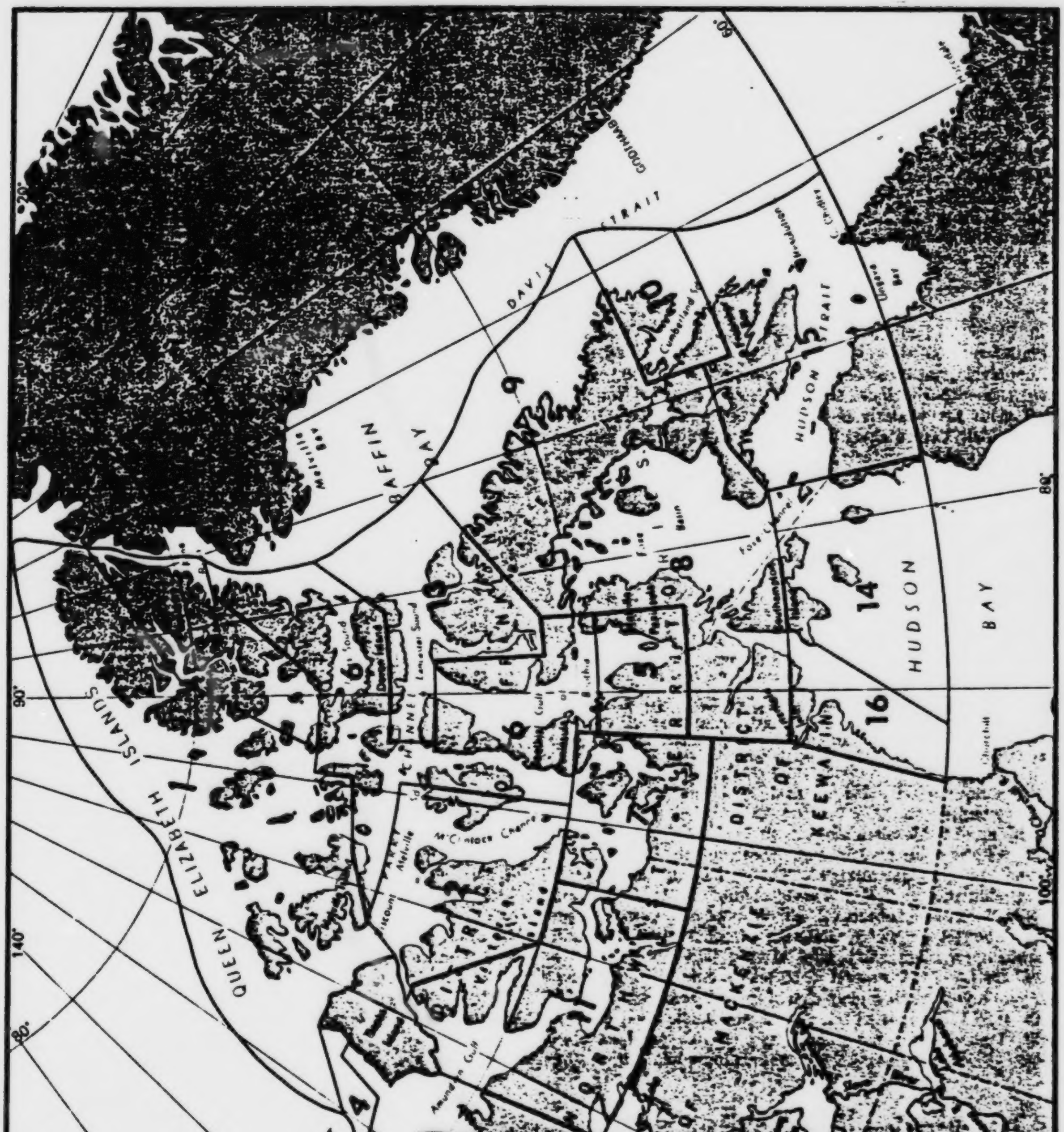
In preparing this diagram, the distances were taken from the ship's log and correspond to the inward route diagrams previously given. The steaming times reflect the proportions of the route spent in the continuous and ramming-mode as shown in the lower part of the diagram and takes into account the monthly variations in route ice thickness as indicated by the first year ice growth curves (Attachment 3.7). The speed of advance for the various ice thicknesses was determined from the ice performance charts given in Section 4 of this report where a thickness of one metre was taken as the dividing line between the continuous and ramming modes. An allowance was also made for the presence of MYR ice and ridging. The net result is that there is not only a significant difference in the route mileage but also a very substantial difference of steaming time throughout the season. This difference is less pronounced at the end of the season, November, when the averaged ice thickness is not as great as at the beginning of the season. Based upon these averages, it would appear feasible to extend the shipping season beyond the end of the present seasonal limit. Sometimes, however, exceptionally heavy ice conditions occur at each end of the season. For instance, in early July 1983, it took more than four days to transit the last 50 miles of Admiralty Inlet into Nanisivik. In November 1984, the vessel became stuck in a ridge for about 2 hours in Lancaster Sound, but was operating at reduced power due to earlier engine problems.

3.5 Summary of findings

The difference in severity indicated in the fore-going description of average route ice conditions suggest that it might be possible to extend shipping operations beyond the end of the present seasonal limit in some years. Certain other considerations would have to be taken into account, however, if the season was to be extended to late November, principal amongst which are ice related shipping hazards such as icebergs, bergy bits and growlers. During the summer months detection and avoidance of these hazards is facilitated by the long daylight hours. However, after August the duration of daylight hours rapidly diminishes. By the beginning of November - at between 70° and 75°N latitude - there is less than 5 hours of daylight and by the end of November, the ship would be operating in a very short period of daylight as the sun would remain continuously below the horizon. Safe navigation in the dark would involve greater dependence on suitable ice detection equipment.

Other environmental factors would also have to be taken into account, for instance, the effect of winds and currents which produce areas of heavy ice accumulation and pressure. A variety of seasonal conditions would have to be considered, therefore, in extending the shipping season but an end of November objective would appear to be attainable in most years.

CASPPR SHIPPING ZONES



CASPPR SHIPPING SEASONS

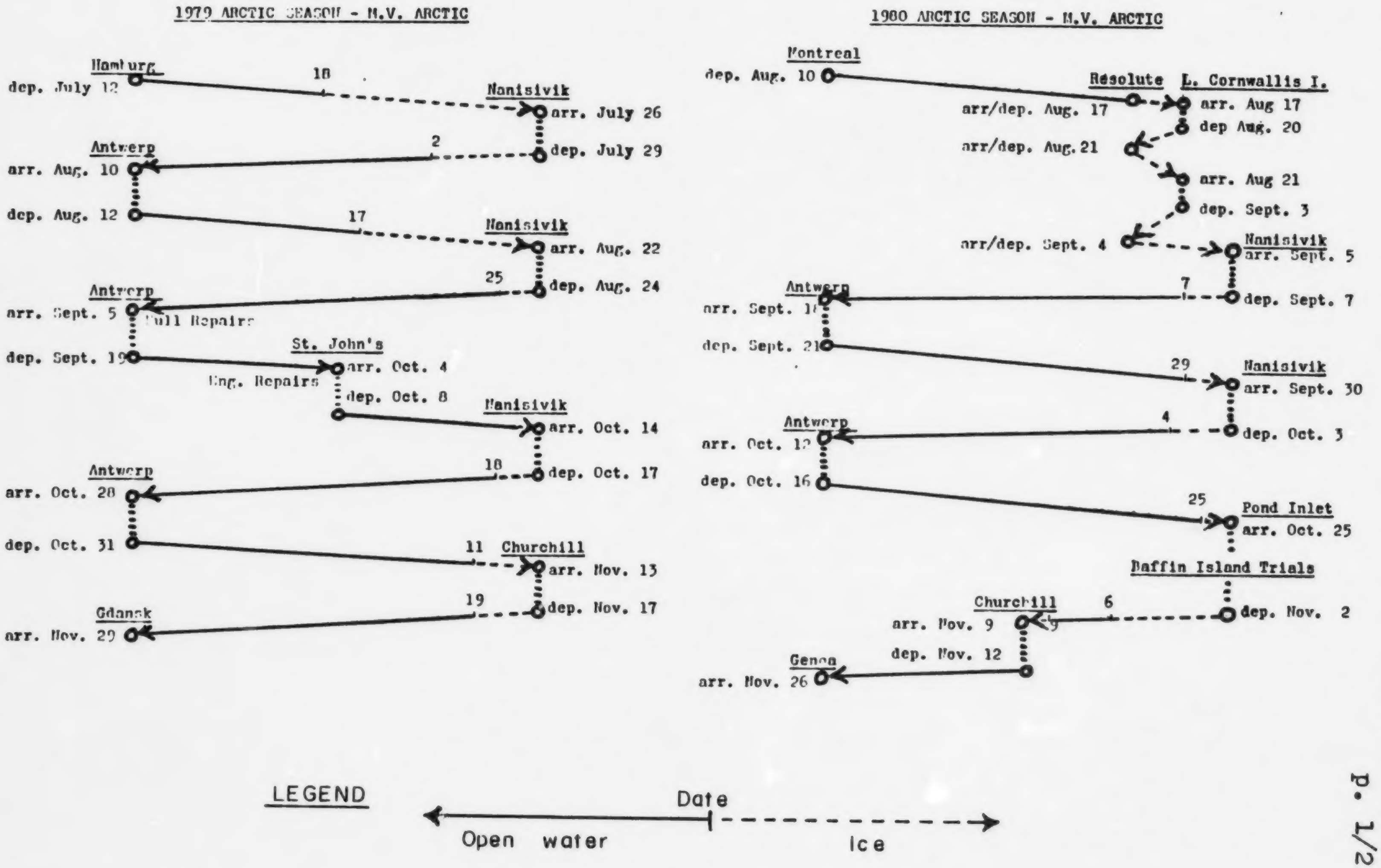
SCHEDULE II

TABLE

Column I Category	Column II Zone 1	Column III Zone 2	Column IV Zone 3	Column V Zone 4	Column VI Zone 5	Column VII Zone 6	Column VIII Zone 7	Column IX Zone 8	Column X Zone 9	Column XI Zone 10	Column XII Zone 11	Column XIII Zone 12	Column XIV Zone 13	Column XV Zone 14	Column XVI Zone 15	Column XVII Zone 16
Arctic Class 10 1.	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
Arctic Class 8 2.	Jul. 1 to Oct. 15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
Arctic Class 7 3.	Aug. 1 to Sept. 30	Aug. 1 to Nov. 30	Jul 1 to Dec. 31	Jul. 1 to Dec. 15	Jul. 1 to Dec. 15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
Arctic Class 6 4.	Aug. 15 to Sept. 15	Aug. 1 to Oct. 31	Jul. 15 to Nov. 30	Jul. 15 to Nov. 30	Aug. 1 to Oct. 15	Jul 15 to Feb. 28	Jul. 1 to Mar. 31	Jul. 1 to Mar. 31	All Year	All Year	Jul. 1 to Mar. 31	All Year	All Year	All Year	All Year	All Year
Arctic Class 4 5.	Aug. 15 to Sept. 15	Aug. 15 to Oct. 15	Jul. 15 to Oct. 31	Jul. 15 to Nov. 15	Aug. 15 to Sept. 30	Jul. 20 to Dec. 31	Jul. 15 to Jan. 15	Jul. 15 to Jan. 15	Jul. 10 to Mar. 31	Jul. 10 to Feb. 28	Jul. 5 to Jan. 15	June 1 to Jan. 31	June 1 to Feb. 15	June 15 to Feb. 15	June 15 to Mar. 15	June 1 to Feb. 15
Arctic Class 3 6.	Aug. 20 to Sept. 15	Aug. 20 to Sept. 30	Jul. 25 to Oct. 15	Jul. 20 to Nov. 5	Aug. 20 to Sept. 25	Aug. 1 to Nov. 20	Jul. 20 to Dec. 15	Jul. 20 to Dec. 31	Jul. 20 to Jan. 20	Jul. 15 to Jan. 25	Jul. 5 to Dec. 15	June 10 to Dec. 31	June 10 to Dec. 31	June 20 to Jan. 10	June 20 to Jan. 31	June 5 to Jan. 10
Arctic Class 2 7.	No Entry	No Entry	Aug. 15 to Sept. 30	Aug. 1 to Oct. 31	No Entry	Aug. 15 to Nov. 20	Aug. 1 to Nov. 20	Aug. 1 to Nov. 30	Aug. 1 to Dec. 20	Jul. 25 to Dec. 20	Jul. 10 to Nov. 20	June 15 to Dec. 5	June 25 to Nov. 15	June 25 to Dec. 10	June 25 to Dec. 20	June 10 to Dec. 10
Arctic Class 1A 8.	No Entry	No Entry	Aug. 20 to Sept. 15	Aug. 20 to Sept. 30	No Entry	Aug. 25 to Oct. 31	Aug. 10 to Nov. 5	Aug. 10 to Nov. 20	Aug. 10 to Dec. 10	Aug. 1 to Dec. 10	Jul. 15 to Nov. 10	Jul. 1 to Nov. 10	Jul. 15 to Oct. 31	Jul. 1 to Nov. 30	Jul. 1 to Dec. 10	June 20 to Nov. 30
Arctic Class 1 9.	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 25 to Sep. 30	Aug. 10 to Oct. 15	Aug. 10 to Oct. 31	Aug. 10 to Oct. 31	Aug. 1 to Oct. 31	Jul. 15 to Oct. 20	Jul. 1 to Oct. 31	Jul. 15 to Oct. 15	Jul. 1 to Nov. 30	Jul. 1 to Nov. 30	June 20 to Nov. 15
Type A 10.	No Entry	No Entry	Aug. 20 to Sept. 10	Aug. 20 to Sept. 20	No Entry	Aug. 15 to Oct. 15	Aug. 1 to Oct. 25	Aug. 1 to Nov. 10	Aug. 1 to Nov. 20	Jul. 25 to Nov. 20	Jul. 10 to Oct. 31	June 15 to Nov. 10	June 25 to Oct. 22	June 25 to Nov. 30	June 25 to Dec. 5	June 20 to Nov. 20
Type B 11.	No Entry	No Entry	Aug. 20 to Sept. 5	Aug. 20 to Sept. 15	No Entry	Aug. 25 to Sep. 30	Aug. 10 to Oct. 15	Aug. 10 to Oct. 31	Aug. 10 to Oct. 31	Aug. 1 to Oct. 31	Jul. 15 to Oct. 20	Jul. 1 to Oct. 25	Jul. 15 to Oct. 15	Jul. 1 to Nov. 30	Jul. 1 to Nov. 30	June 20 to Nov. 10
Type C 12.	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 25 to Sep. 25	Aug. 10 to Oct. 10	Aug. 10 to Oct. 25	Aug. 10 to Oct. 25	Aug. 1 to Oct. 25	Jul. 15 to Oct. 15	Jul. 1 to Oct. 25	Jul. 15 to Oct. 10	Jul. 1 to Nov. 25	Jul. 1 to Nov. 25	June 25 to Nov. 10
Type D 13.	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 10 to Oct. 5	Aug. 15 to Oct. 20	Aug. 15 to Oct. 20	Aug. 5 to Oct. 20	Jul. 15 to Oct. 10	Jul. 1 to Oct. 20	Jul. 30 to Sep. 30	Jul. 10 to Nov. 10	Jul. 5 to Nov. 10	Jul. 1 to Oct. 31
Type E 14.	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 10 to Sep. 30	Aug. 20 to Oct. 20	Aug. 20 to Oct. 15	Aug. 10 to Oct. 20	Jul. 15 to Sep. 30	Jul. 1 to Oct. 20	Aug. 15 to Sep. 20	Jul. 20 to Oct. 31	Jul. 20 to Nov. 5	Jul. 1 to Oct. 31

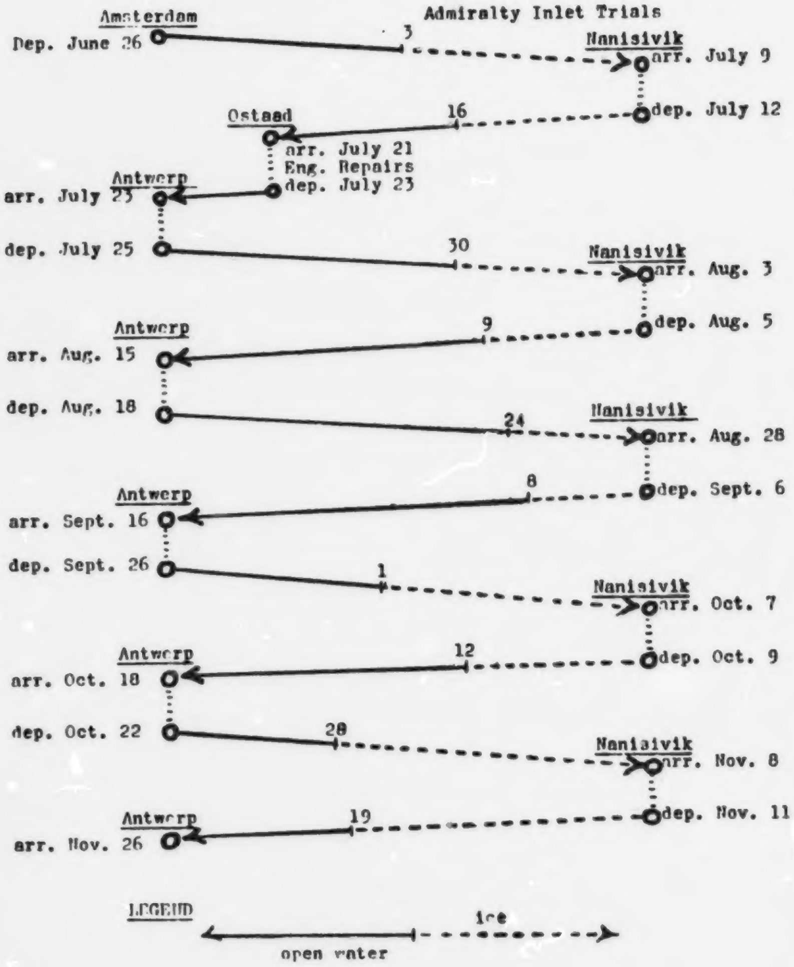
ATTACHMENT 3.2
p. 1/2

MV ARCTIC VOYAGE SCHEDULES



MV ARCTIC VOYAGE SCHEDULES

1981 ARCTIC SEASON - M.V. ARCTIC

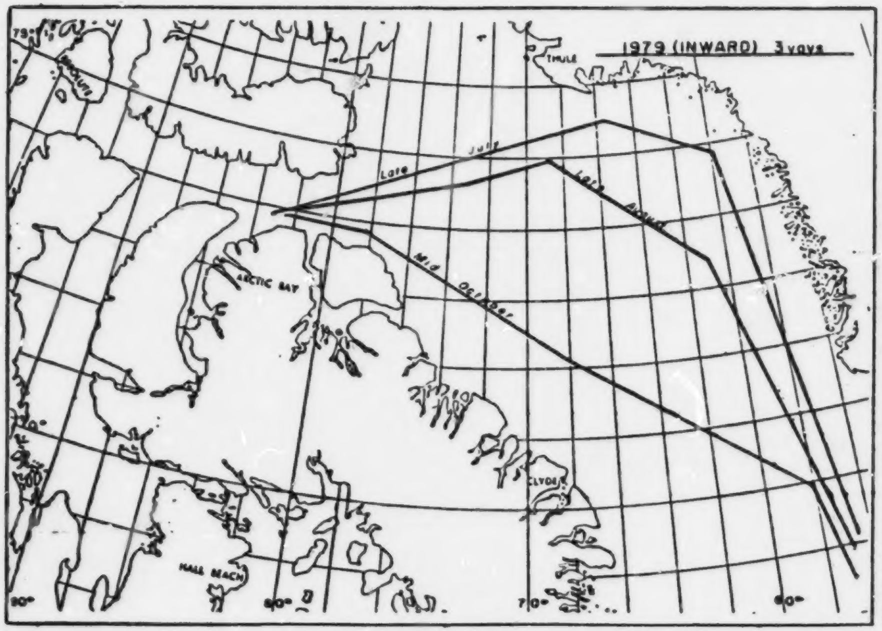


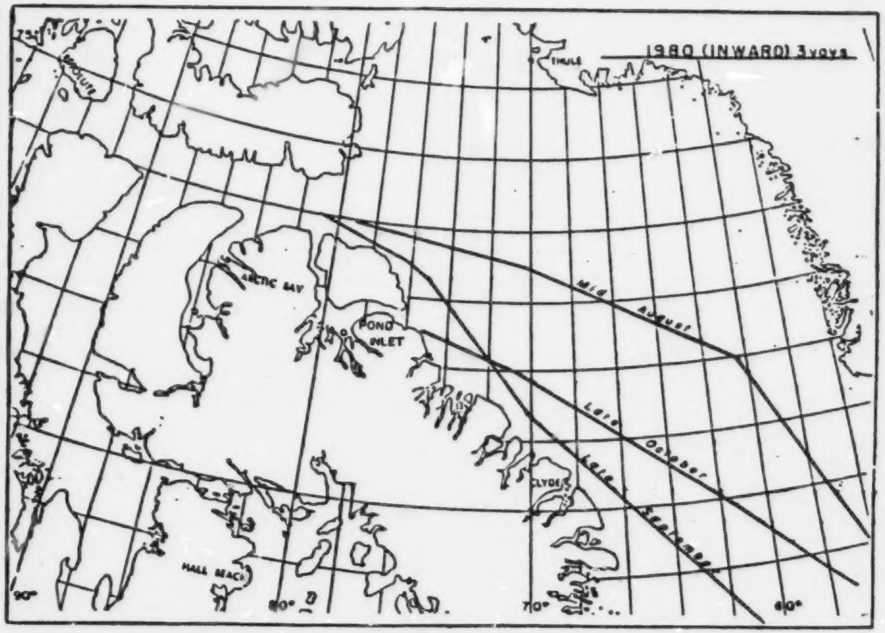
MV ARCTIC VOYAGE SUMMARIES

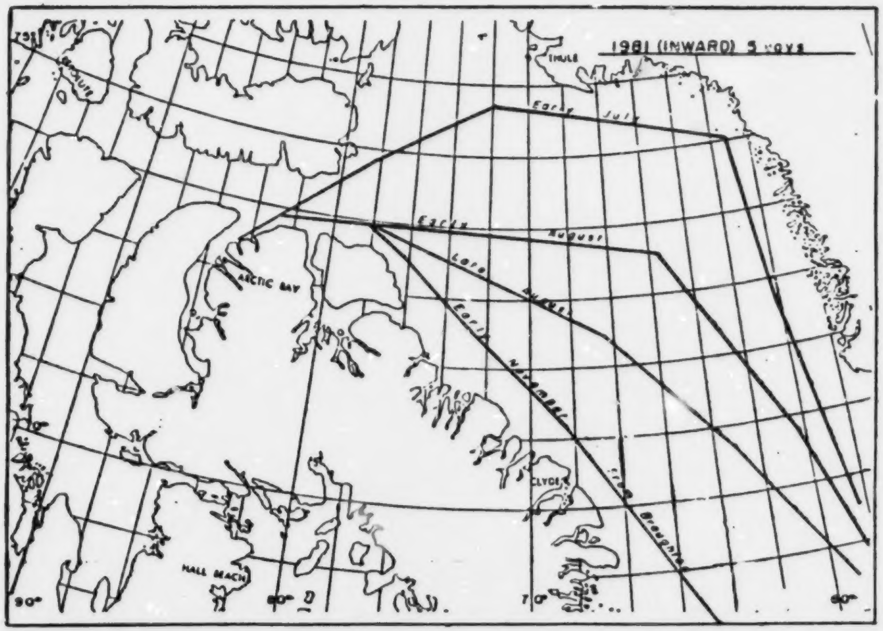
	Arctic Season (Days)			
Passage Time	1979	1980	1981	Total
Ice affected	19	14	58	91
Open Water	86	56	59	201
Total Seatime	105	70	117	292
Total Porttime	35	33	39	107
Total Season	140	103	156	399
Ice % of Seatime	18%	20%	49%	29%

ATTACHMENT 3.3

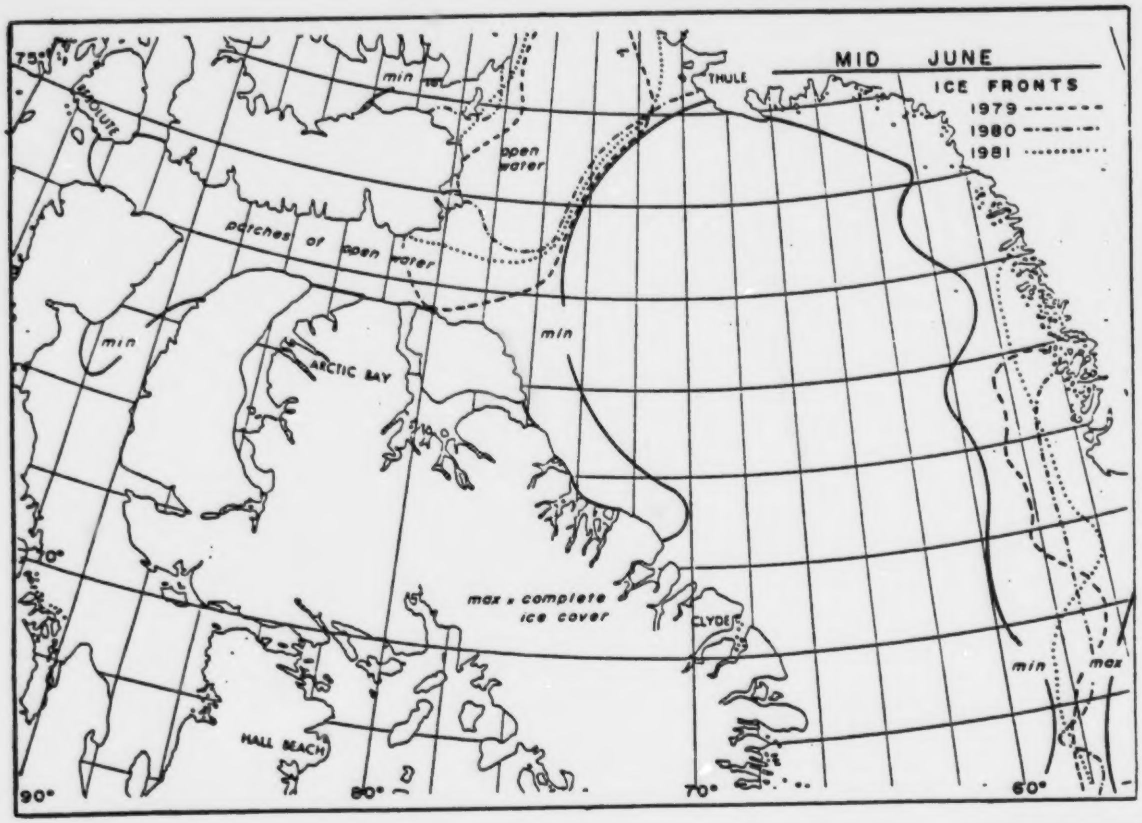
MV ARCTIC -
MONTHLY ROUTES

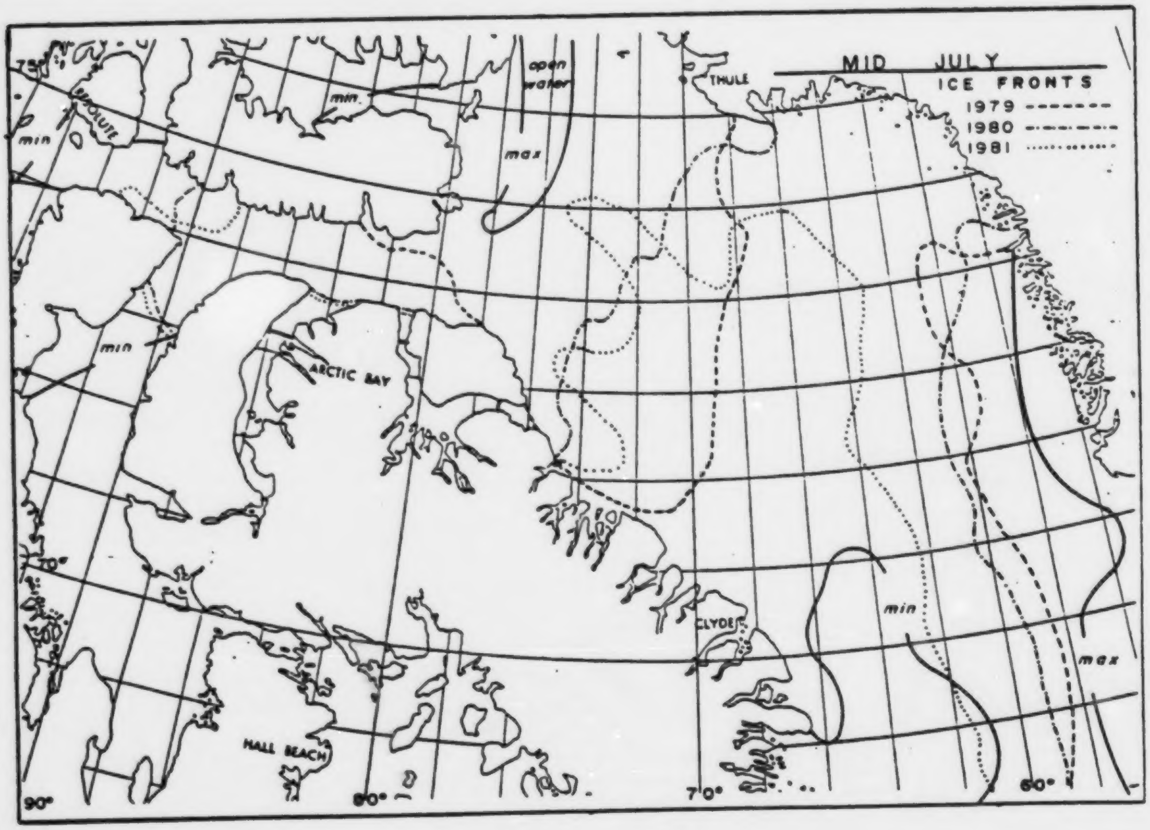




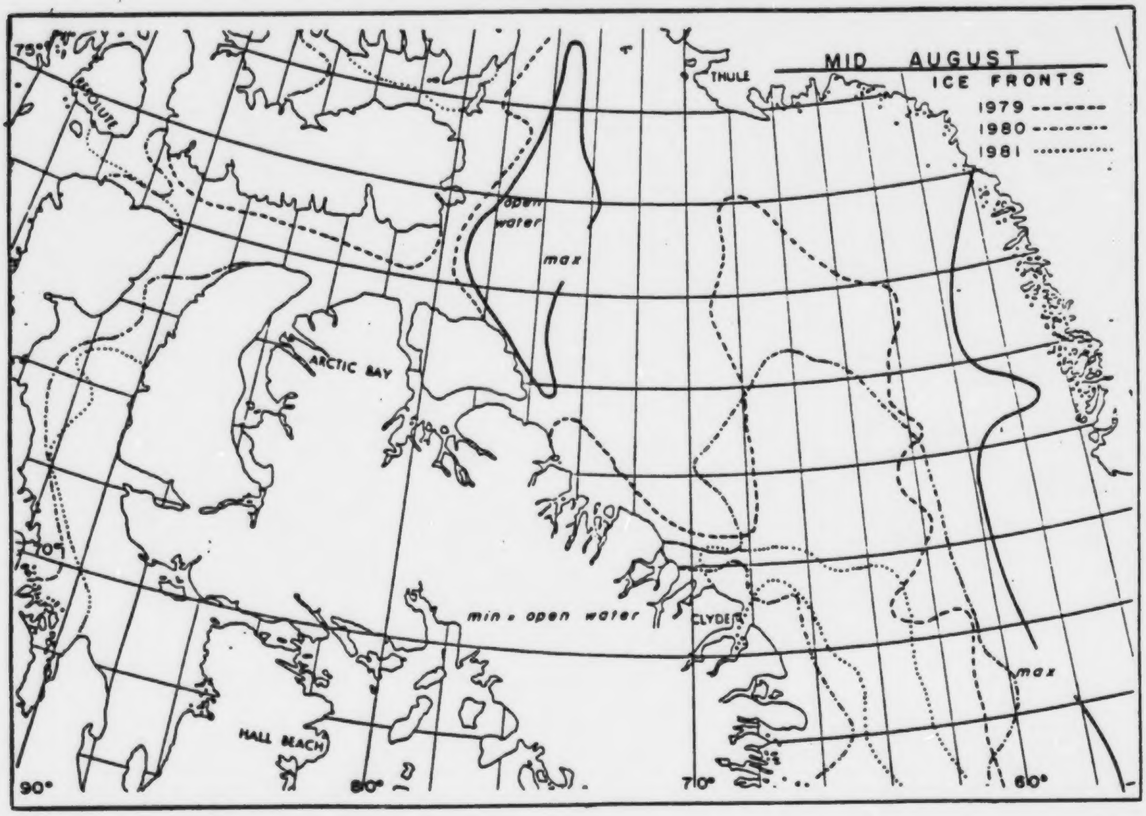


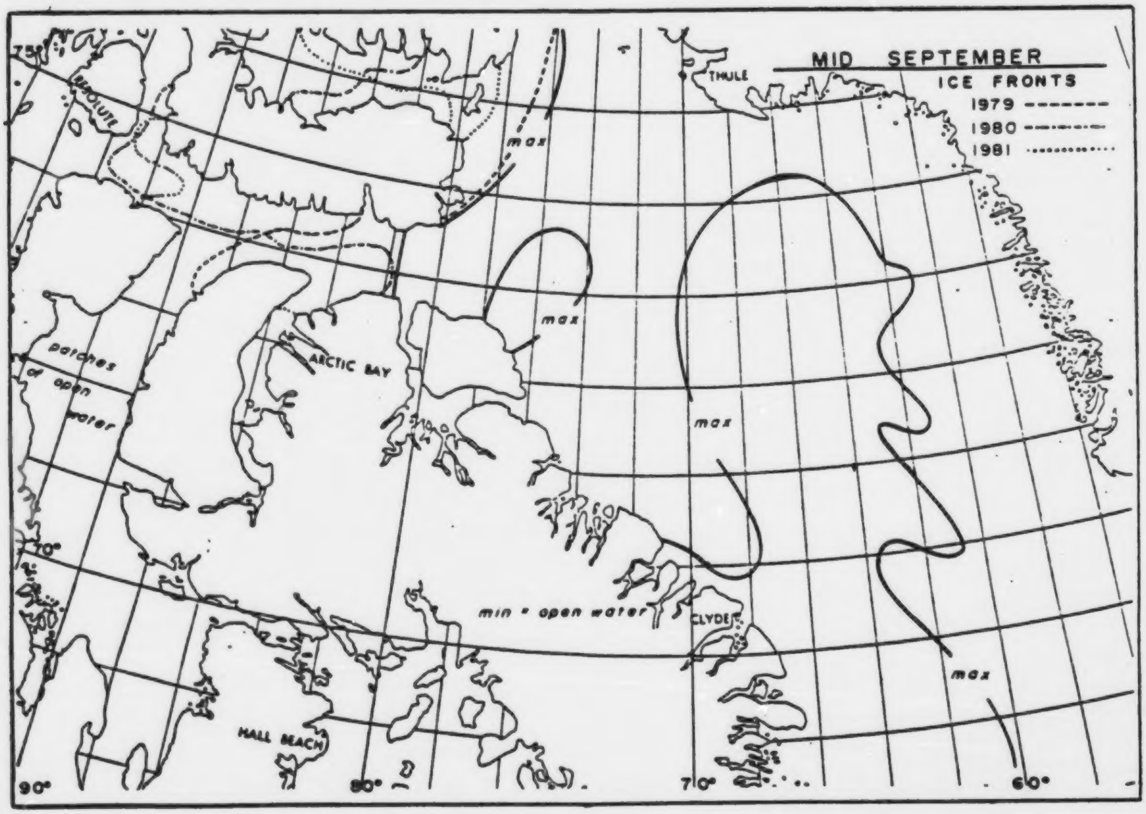
MONTHLY ICE FRONTS



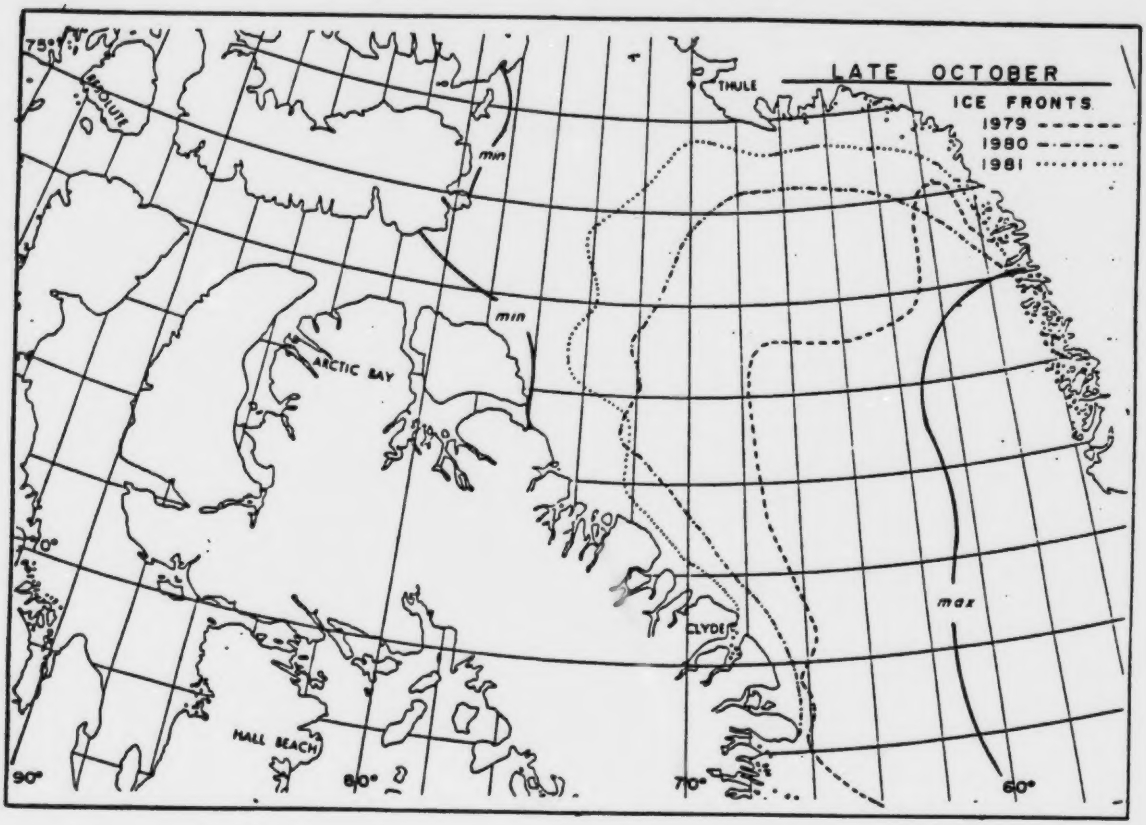


MONTHLY ICE FRONTS

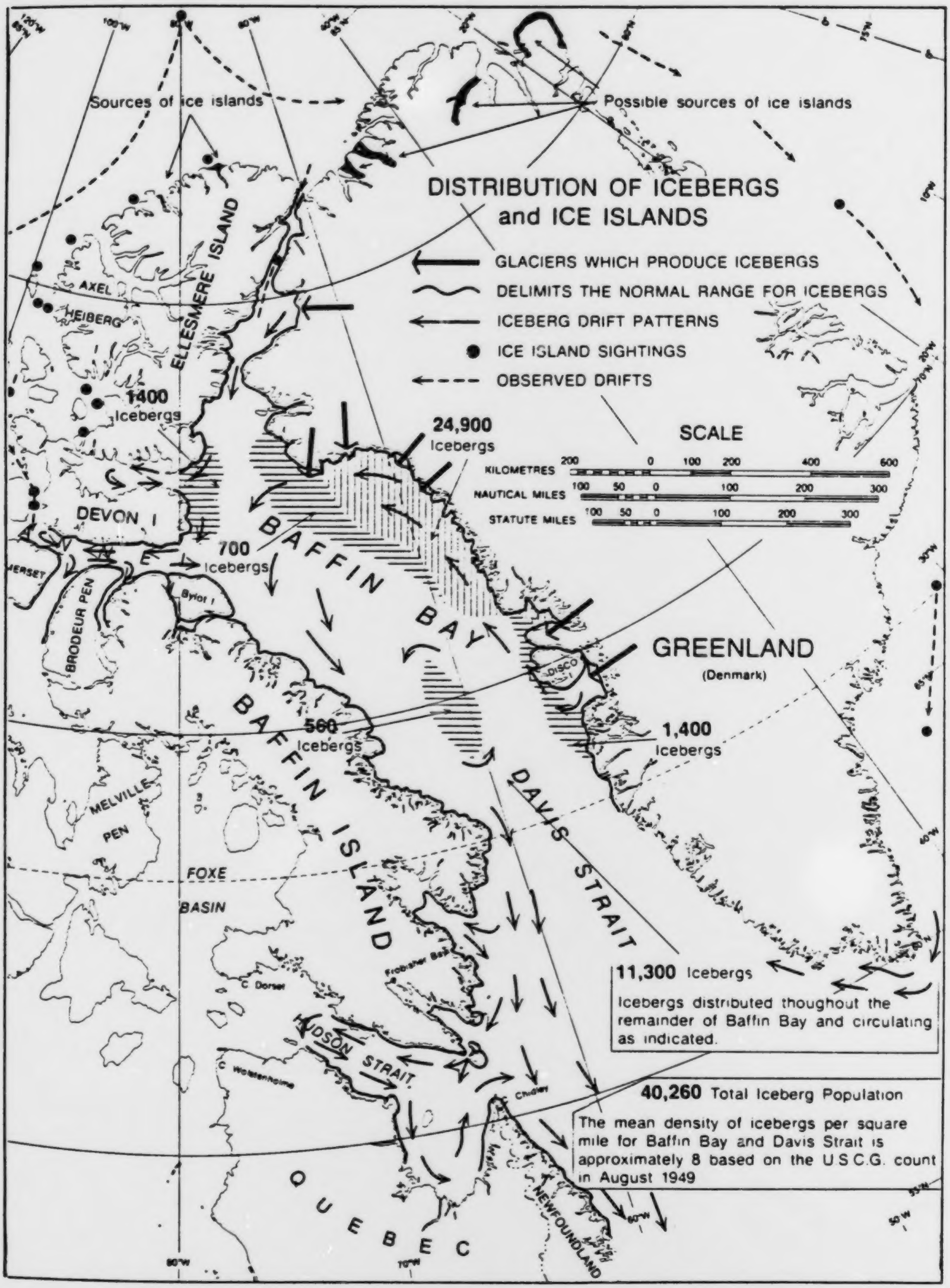




MONTHLY ICE FRONTS

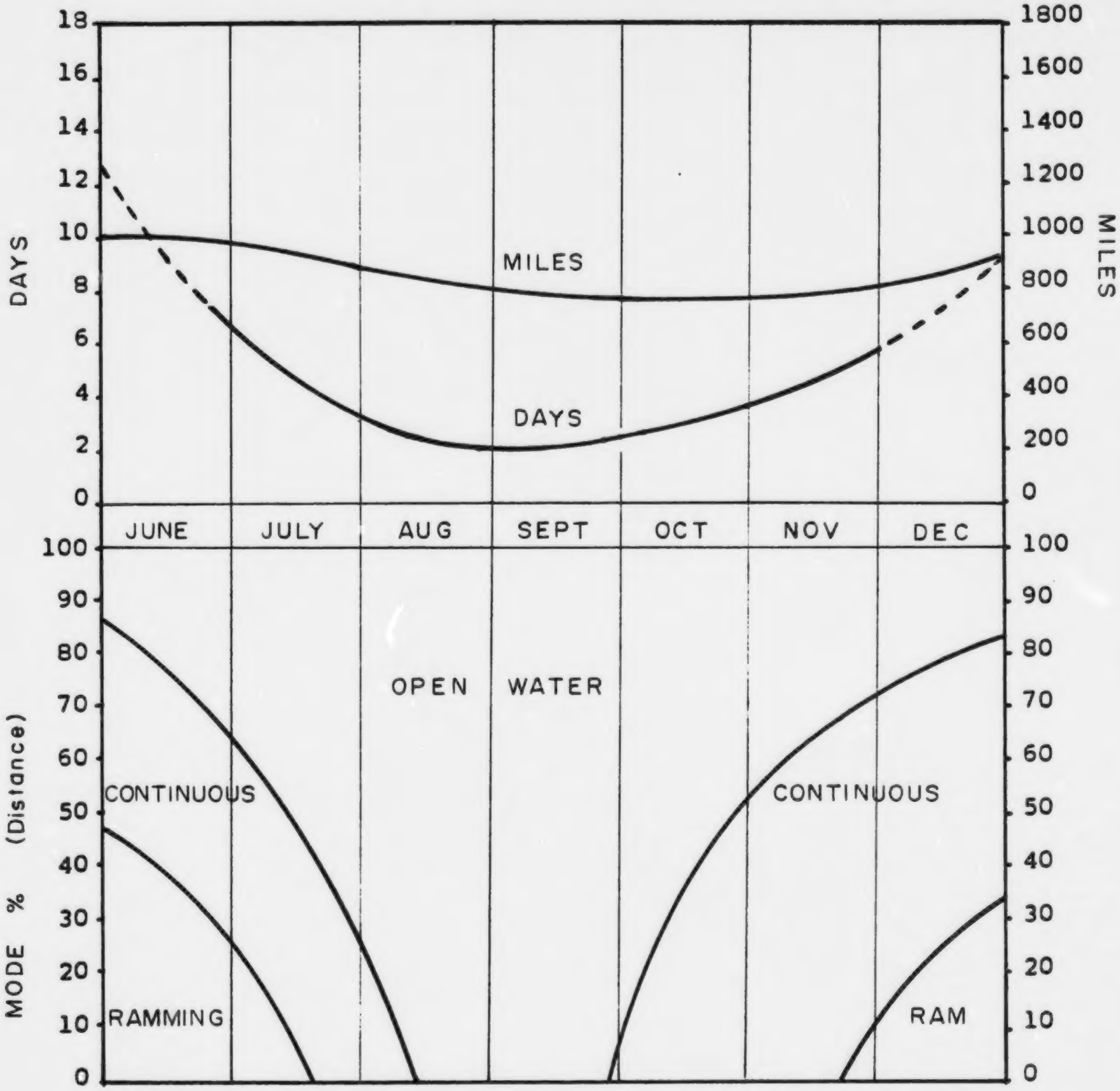


ATTACHMENT 3.5


DISTRIBUTION OF ICEBERGS and ICE ISLANDS
GLACIERS WHICH PRODUCE ICEBERGS
DELIMITS THE NORMAL RANGE FOR ICEBERGS
ICEBERG DRIFT PATTERNS
ICE ISLAND SIGHTINGS
OBSERVED DRIFTS
SCALE
KILOMETRES 200 0 100 200 400 600
NAUTICAL MILES 100 50 0 100 200 300
STATUTE MILES 100 50 0 100 200 300
Sources of ice islands
Possible sources of ice islands
ELLESMERE ISLAND
AXEL HEIBERG
1400 Icebergs
24,900 Icebergs
700 Icebergs
560 Icebergs
1,400 Icebergs
DEVON I
SOMERSET
BRODEUR PEN
Bylot I
BAFFIN BAY
GREENLAND (Denmark)
DISCO
BAFFIN ISLAND
DAVIS STRAIT
MELVILLE PEN
FOXE BASIN
Frobisher Bay
C Dorset
HUDSON STRAIT
C Wolstenholme
C Chidley
QUEBEC
NEWFOUNDLAND
120°W
100°W
80°W
70°W
60°W
50°W
11,300 Icebergs
Icebergs distributed thoughout the remainder of Baffin Bay and circulating as indicated.
40,260 Total Iceberg Population
The mean density of icebergs per square mile for Baffin Bay and Davis Strait is approximately 8 based on the U.S.C.G. count in August 1949

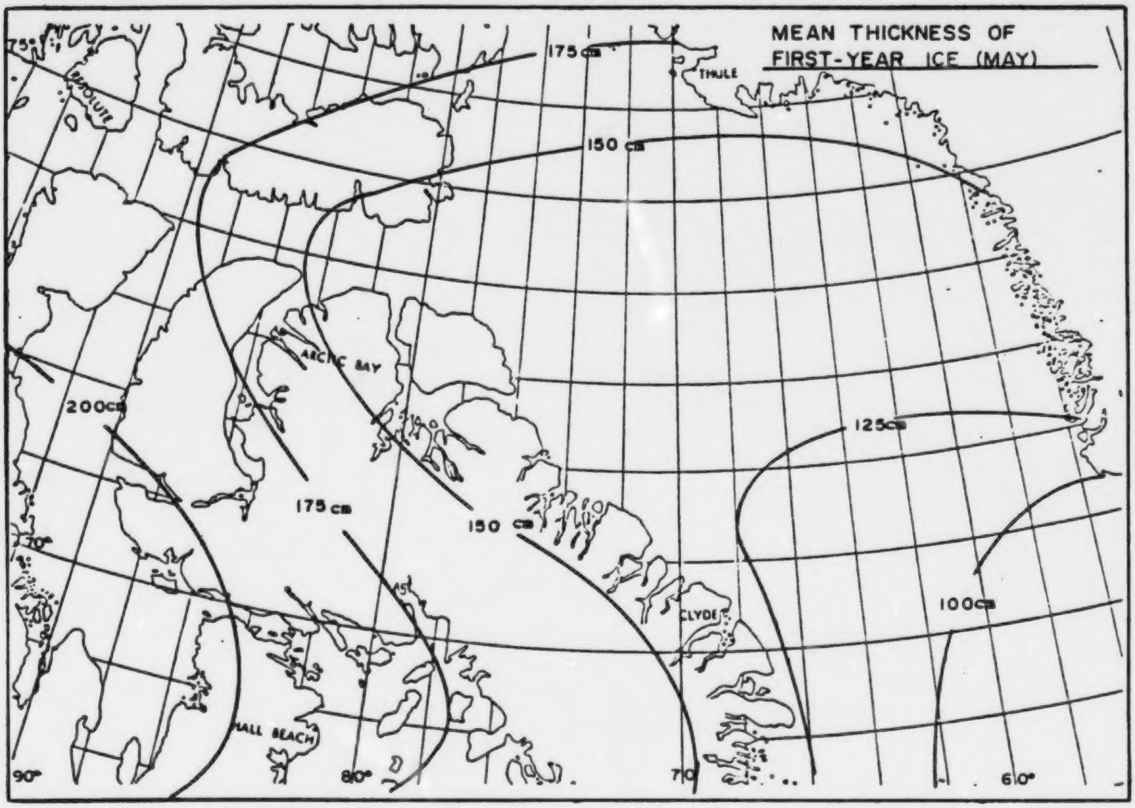
MONTHLY DISTANCES AND TIMES

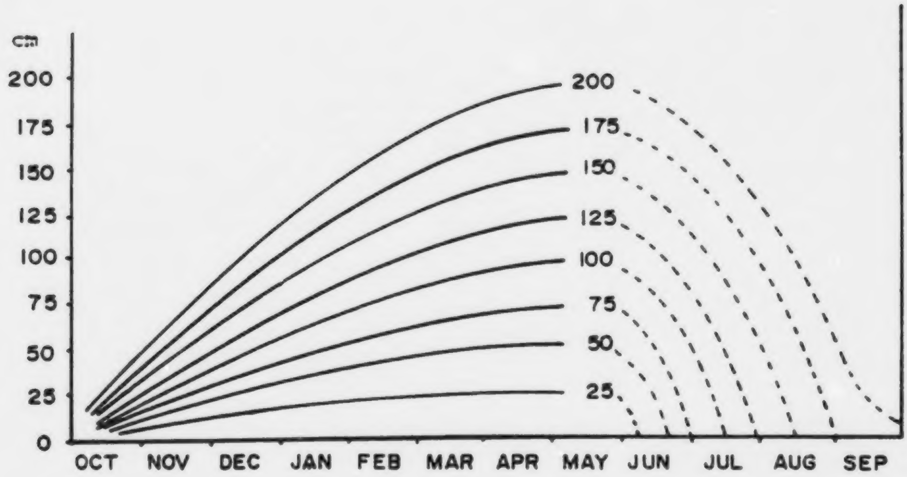
ARCTIC CIRCLE TO NANISIVIK



ATTACHMENT 3.7

FIRST YEAR ICE
MONTHLY MEAN THICKNESS





FIRST-YEAR ICE GROWTH CURVE

SECTION 4

ICE-TRANSITING PERFORMANCE

4.1 Introduction

The ice-transiting performance capabilities of the MV. Arctic have been evaluated under three separate modes of progression through ice, namely, continuous-mode, ramming-mode and manoeuvering-mode. It is worthy of mention that no formal criteria have been laid down in the rules and regulations or elsewhere which define the ice-transiting requirements of ice classed vessels. Accordingly, the design of such vessels is accomplished as the best compromise between mass, form and power of which mass (predominantly controlled by deadweight in the case of a cargo vessel) is pre-determined by the requirements of a particular commercial service. There is no stipulated baseline against which a particular design can be compared but, instead, the past experience of earlier designs is used to best advantage to continually improve the state-of-the-art with respect to ice-transiting performance in the various modes. Consequently, each new design tends to be the outcome of fundamental considerations based upon the best of analytical principles and empirical results in which model-testing supported by full-scale testing plays an important role. This sequence of events has been followed in the case of the MV. Arctic and the results obtained from the scientific program are described herein.

4.2 Continuous-mode performance

4.2.1 General background

As a background to the analysis of the continuous-mode performance of the MV. Arctic in various types of level ice, a review was made of existing knowledge and previous attempts to formulate equations for predicting the resistance of ice to the motion of a ship. Level ice conditions may be divided into three main classifications as follows:

a) continuous level sheet ice,
b) pack ice or concentrations of ice floes,

c) channels previously broken in sheet ice.

Historically, most research has been carried out on the resistance of continuous sheet ice, probably because it is more amenable to rigorous treatment and also because this is the predominating form of ice in the Baltic Sea where most early full-scale tests were undertaken by Russia and Finland.

Although equations for the resistance of sheet ice have been presented by researchers since the end of the nineteenth century, it was not until 1968 that a formal analytical approach to the problem was proposed and became generally accepted. This was based on the thesis that R_i, the resistance of ice to the motion of a ship, is made up of three main components.

$$R_i = R_b + R_s + R_v$$

where,

R_b is the resistance due to breaking the ice which is independent of velocity;

R_s is the resistance due to submerging the broken ice which is independent of velocity;

R_v is velocity dependent resistance.

The total resistance R_t of the ship, therefore consists of R_i as defined above plus R_{ow} which is the open water resistance.

The selection of parameters forming each of the above three terms of the ice resistance equation is very much a matter of judgement and differs with the various authorities. These will include, for the ship, various dimensions and form coefficients and, for the ice, various physical and mechanical parameters as well as frictional effects between the ice and the ship. As the result, there is significant divergence between various predictions of ice resistance and to the proportions to be assigned to the three terms of the resistance equation. The net result is that ice resistance predictors tend to be ship-specific with very limited potential for wide general application.

The main advance in recent years is the realisation that the ice-breaking component of total resistance is greater than previously expected. Accordingly, much technological consideration has been given to bow shape, including White, Spoon and Waas forms, as well as various means to minimise hull/ice friction. The MV. Arctic incorporates a modified White bow and has an air bubbler system and special hull coating to reduce friction, all of which represented the best of ice-transiting technology at the time of her design.

4.2.2 Performance in continuous sheet-ice

As previously indicated, the development of general equations to predict the performance of ships in ice is still an inexact science. Nevertheless, it was decided to use the MV. Arctic database in an effort to develop a semi-general resistance equation using an existing formulation. A total of some forty formulations by various authorities were examined and short-listed to two types as follows:

A) Equations based on the historical principle that ice resistance consists of three main components which could be treated semi-statically.

B) Equations more recently developed and based on quasi-static analysis which is then modified by dynamic considerations or based upon dynamic considerations alone.

The testing process revealed that selected formulations both of Type A and Type B were reasonably representative of the MV. Arctic level ice resistance. In the final analysis, however, it was concluded that, because Type B formulations were relatively new and untried, a Type A formulation was adopted with suitable modifications.

The continuous-mode performance of the MV. Arctic as given by the resultant equation is shown in Attachment 4.1 in the form of the relationship between power, speed and ice thickness. This allows for a flexural strength of 350 kPa which is generally representative of the first year arctic ice encountered during the voyages.

It is evident that the MV. Arctic has a continuous-mode creep capability in ice of approximately 1 metre in thickness. This is more than would normally be expected of an Ice Class 2 vessel and is due to a number of design factors, including power, which are addressed later in this section.

4.2.3 Performance in broken channels

As would be expected, the speed of advance of a vessel operating in a previously broken channel or loose pack ice is greater than the speed which could be achieved through an unbroken ice sheet. The diagram in Attachment 4.2 shows the variation of ship speed in broken channels containing ice pieces of different sizes. The curves are bounded by the speed in unbroken ice and open water. The broken channel speed curves have been developed from the data obtained when the MV. Arctic was following an icebreaker of greater breadth through ice 0.4 m thick. It is evident that significant improvements in speed of advance can be achieved in a broken channel. The diagram indicates a high level of speed sensitivity to the size of the broken pieces which in turn is controlled by the icebreaking efficiency of the lead icebreaker. The extent to which the higher speeds can be fully utilised by the following ship, however, depends upon the vessel's structural strength to withstand floe impacts which subject is addressed in Section 6 of this report.

4.3 Ramming-mode performance

4.3.1 General background

A vessel such as the MV. Arctic, unlike dedicated icebreakers, is not intended for ramming but will use the ramming-mode of progression judiciously as an assist to movement through ice within the limits of her structural strength. In the design and operation of such commercial ice-transiting vessels, it is the transition zone between the continuous-mode and the ramming-mode which is of most interest whereby the vessel can employ tactics to increase her speed of advance without imposing significantly higher loads on her structure. When the ice cover exceeds the transition zone conditions, there is no alternative to the ramming-mode which, on occasion, will have to be adopted even when the vessel is assisted by an icebreaker. Consequently, consideration has to be given to the ramming-mode capability of the vessel and the strategy of ramming. In order to investigate these matters, ramming tests at moderate impact speeds were conducted in Admiralty Inlet in July 1981 and, together with various other ramming events, were analysed to develop a ramming performance profile for the MV. Arctic.

4.3.2 Ramming cycle

The process of ramming consists of a sequence of events in which the vessel backs away, accelerates and charges the ice to penetrate a certain distance depending upon the speed of impact. This is a repetitive process in which the ship's overall speed of advance is a function of the cumulative penetration distance achieved over several rams and the total elapsed time. The sequence of events for each ram can be idealized as shown in Attachment 4.3 and consists of two inter-active cycles, namely, engine or pitch control action and ship speed response. Optimum speed of advance depends upon optimisation of the action cycle to achieve the best response cycle. This requires that pitch activation should be such as to permit the vessel to reverse and accelerate to the desired impact speed in the shortest time and that the engines should assist the penetration phase as shown in the attachment. Some examples of extended action cycles in which ahead power is used hesitantly, and which resulted in less than optimal speeds of advance are shown in Attachment 4.4. Accordingly, the database was carefully combed to remove such effects in the process of developing a ramming-mode performance profile for the MV. Arctic.

4.3.3 Ramming profile and strategy

The ramming-mode capabilities of the MV. Arctic were determined from the database after optimisation of the components of the ramming cycle as previously described. For each component, the ramming events were evaluated with respect to ice thickness, ahead and astern power levels, prompt execution of the action cycle and limiting speeds in the broken ice channel. Two main ice thicknesses, 1.6 m and 2.5 m, dominated the database and were used to optimize the speed of advance and fuel consumption characteristics of the MV. Arctic. The result is provided in Attachments 4.5 (a) and (b). These diagrams show that speed of advance and fuel consumption follow the same trend and are optimal at a particular impact ramming speed for a particular ice thickness. The effect of power level was also examined and led to the conclusion that the best results are obtained when full ahead power and three quarter power astern is used in the ramming cycle. It is noteworthy that the CASPPR criteria calls for a 70% astern power capability in ice class ship machinery.

The achievement of the above optimum ramming performance profile at the stated power levels is dependent upon the adoption of an optimal ramming strategy related to the action cycle. This means that pitch control must be decisively exercised to ensure that the ship will back and accelerate timeously over just the right distance needed to achieve the required impact speed. The strategy to achieve this for the MV. Arctic is given in Attachment 4.6 for the optimum power levels. The diagram shows the optimum impact speed for each ice thickness with the required backing distance and the astern time needed from commencement of backing until commencement of pitch reversal to accelerate.

A further aspect of ramming strategy is concerned with the use of thrust during the penetration phase. Pitch shedding, too early, results in a significant loss of penetration distance by as much as 50% in 1.5 m ice. The loss is less pronounced in thick ice so that, in ice over about 2.5 m thickness, the economics involved are such that the distance advantage gained from maintaining thrust is more than offset by the additional fuel consumed.

4.3.4 Transition zone

The transition zone between the continuous-mode and the ramming-mode of progression is of particular interest in maintaining the best speed of advance. This is shown in Attachment 4.7 (a) which indicates that there is a distinct advantage in changing to the ramming-mode above an ice thickness of about 1 metre, even though the continuous-mode is still possible. In this zone, progression is by means of a series of long rams where penetration is assisted by use of the mass of the vessel at high impact speeds. The net effects on time and distance result in a better speed of advance than would be possible under slow continuous movement.

4.3.5 Ultimate ramming capabilities

Extrapolation of the results previously obtained indicates that the ultimate ramming capability of the MV. Arctic is reached in ice of about 3.5 metres thick. The extent to which such ultimate capabilities could be pursued, however, would be more a matter for structural consideration which is addressed later in this report.

Ridge penetration ability, as an expression of ultimate continuous-mode capability, is of direct and on-going relevance for all ice-transiting vessels. Accordingly, the ability of the MV. Arctic to breach a ridge in a single pass without being stopped has been investigated. The ridge-breaching profile of the MV. Arctic is given in Attachment 4.7 (b) for two thicknesses of first-year ice. The curves, in each case, delineate the upper boundary of ridge size which the vessel could just breach without stopping when approaching at the continuous-mode speed through field ice of the indicated thickness. Ridges above the delineated size would bring the vessel to a halt and require one or more rams before total penetration could be achieved. The diagram also assumes that the separation between limiting ridges would be such as to provide sufficient distance for the vessel to resume continuous-mode speed before encountering the next ridge.

By way of comparison, the diagram also shows ridge breaching capabiliites in the ramming-mode. The curves, in each case, delineate the upper boundary of ridge size which the vessel could breach in a single ram when approaching in the ramming mode through field ice of the indicated thickness. In these cases, the broken channel approach (ramming-mode) permits a higher impact speed than with continuous-mode and so increases the ridge breaching capability.

4.4 Manoeuvering performance

4.4.1 General background

The degree of manoeuverability required by an ice-transiting vessel is dictated largely by the requirements of the mission for which the vessel is used. In the case of a dedicated icebreaker, the mission incorporates many pathfinding tasks including, assistance to ships, flood control, search and rescue, etc., all of which demand a high degreee of manoeuverability. In the case of an icebreaking commercial vessel, such as the MV. Arctic, the requirements are less demanding and call mainly for reasonable qualities for maintaining a straight course and for performing course alterations in ice. The more rigorous needs, such as vessel extraction when beset in ice and docking in the confines of an icebound harbour, whilst calling for higher degrees of manoeuverability also have other solutions including icebreaker or tug assistance. The qualities desired of the commercial vessel, therefore, are those sufficient to provide her with a reasonable degree of manoeuvering self-sufficiency so that dependence on assistance is minimized. The MV. Arctic manoeuvering qualities have been evaluated accordingly and, since this subject has hitherto received relatively little attention, the results are of considerable interest.

4.4.2 Directional stability in ice

The MV. Arctic exhibits positive directional stability when moving ahead in open water. This means that, with the helm held amidships, the ship always tends to return to her mean course when deflected port or starboard under normal oscillations. This is a desirable feature of all ship designs. An investigation was carried out to determine the directional characteristics of the MV. Arctic when operating in various ice conditions. As far as it has been possible to determine from the somewhat limited database, the relationship between helm action required to maintain direction within a small range of deflections about the mean heading is shown in Attachment 4.8 for various ice regimes. The diagram indictes that in ice up to one metre thick, which marks the upper limit of her continuous-mode capabilities, it is possible to hold the vessel within 2° - 3° of her mean course in level ice with helm action no more than 15° about amidship. Where the ice cover includes some multi-year floes, the same helm action can seem to hold the vessel within 6° of the mean course. At the upper limit of the ramming-mode, three metres of ice, helm action not exceeding 25° about amidships, appears to be adequate for reasonable directional stability. A full quantitative assessment of these results is not possible beyond the fact that helm action seems to vary linearly rather than exponentially with ice thickness. Qualitatively, a fair conclusion is that the MV. Arctic does not impose heavy demands on her helsman in order to maintain her course in moderate ice conditions.

4.4.3 Turning in ice

The ability of a ship to turn in ice is an important characteristic from a navigational and a safety point of view which include various course alteration, pathfinding, collision avoidance and docking needs. Accordingly, an investigation was carried out to determine the turning circle characteristic of the MV. Arctic starting with open water and with increasing ice thickness. Under full helm and full power, the turning circle radius expressed in ship lengths (R/L) is shown in Attachment 4.9 and varies from about 2½ ship lengths in open water to about 20 ship lengths in one metre ice which is the upper limit of her continuous-mode capability. The diagram also shows the probable subdivision of turning energy expended in breaking and clearing the ice cover involved. The effects on these quantities when the bubbler is used or the ship is heeled are addressed later in sub-section 4.5 and 4.6 of this report.

The investigation of turning characteristics has revealed a number of noteworthy features. The above mentioned diagram indicates that the radius of turn increases linearly with ice thickness. When this is coupled with the fact that ship resistance (and hence transiting time) increases almost as the square of ice thickness, the net result is that turning time increases almost as the cube of the ice thickness. This means that in collision avoidance tactics, stopping is more effective than turning when the ice is greater than a nominal thickness.

Another interesting finding of the study is that the turning radius appears to increase only by about 10% with the helm at 20° instead of the full 35° rudder. The reason for this is not fully understood but is believed to indicate the existence of a critical rate of turn in ice, beyond which resistance to turning rises more rapidly than the turning moment obtained from increasing the rudder angle.

Finally, it has been concluded that in any particular ice thickness, the radius of turn decreases progressively as the vessel moves around the turning circle. This is most noticeable in the second semi-circle and is believed to be due to weakening of the ice resulting from crack propagation back to the original broken track left by the ship as she approached the turn.

4.4.4 Rudder torque

The 1972 CASPPR provisions which were in effect when the MV. Arctic was designed used a specified ship speed in open water as the criterion for determining rudder and steering gear strength for an ice class vessel. Using that basis for sizing the rudder stock results in a stock diameter of about 350 mm, able to withstand a permissible torque of 535 kNm without yield. The highest recorded value of torque found in the available database was 509 kNm which approaches so close to the above permissible limit that there seems to be very little margin of safety. In actual fact, however, other criteria were incorporated in the determination of rudder stock size for the MV. Arctic which resulted in an "as-fitted" stock diameter of 445m and more than doubled the permissable torque to 1140 kNm. This appears to provide for a good safety margin but the extent of adequacy cannot be precisely determined from the limited database available for rudder torque.

It should be noted that the 1972 CASPPR provisions on steering gear strength were revoked in 1978 and replaced by provisions which, although definitive, are less explicit for the designer. The Russian rules, however, are most explicit and would require the rudder stock to have nearly three times the torsional strength than the stock fitted to the MV. Arctic or about six times that of the original CASPPR requirements. Accordingly, there is a need to clarify the rudder and steering gear strength requirements for ice classed vessels.

4.5 Effect of hull geometry

The MV. Arctic is fitted with a "White" bow of the type developed for the SS Manhatten. A particular feature of the bow is a low stem angle as measured from the waterline which is 30° in the case of the MV. Arctic, but larger than the SS Manhatten. Bow design seeks to achieve an optimum relationship between, stem angle, waterline entrance angle, and flare angle (Attachment 4.10) so as to produce a good combination of ice cutting, bending, and clearing qualities. It would be expected that an even smaller stem angle and an increase in flare angle with an appropriate modification of entrance angle would tend to improve the icebreaking qualities of the MV. Arctic. For example, the flare angle of the bow decreaes from about 50° at the stem to 0° at the shoulder and Section 6 of this report reveals that high ice pressures occur in the region of the shoulders indicative of poor icebreaking qualities at that point.

Ice is much weaker in bending than in crushing and thus it is evident that flare angle which produces ice bending is important. Various authorities believe that flare should not be less than 15° at any point along the ship and in any case should not be less than that dictated by a relationship with the hull-ice friction coefficient. A single impression of the effect of flare was obtained from the manoeuvering trials where the simulation of flare, produced by a 5° heel (inwards), resulted in about 70% reduction in the radius of the turning circle in thick ice.

In the ramming-mode, it has been noted that the MV. Arctic has a tendency to become stuck at the end of a ram and is sometimes difficult to extract. This tendency is reduced when the vessel is trimmed by the stern, thus increasing the stem angle. Trim also produces an associated increase in flare angle so that the combined effects are difficult to separate. It is evident, however, that trim resulting in a change of hull geometry, improves the MV. Arctic ramming qualities.

The shape and other dimensional (draft) characteristics of the MV. Arctic appear to be conducive to good ice clearing qualities in the sense that there are relative few and only minor impacts of ice blocks on the propeller and rudder. The propeller is protected by a nozzle so that only small ice pieces can be ingested and there is little evidence of aperture-masking by large ice blocks.

Finally, the extent to which changes in hull geometry would affect performance has to take into account open-water as well as ice-transiting capabilities. Geometrical changes which might result in a longer bow also have to keep sight of length restrictions to suit the Seaway dimensions. A more efficient icebreaking form which requires less power may reduce the ship's manoeuvering qualities where turning ability is dependent upon a combination of thrust and rudder. A number of inter-related effects have to be considered, therefore, in obtaining the best advantages of hull geometry.

4.6 Effect of friction

The MV. Arctic is provided with two means of reducing hull-ice friction, namely

- an Inerta 160 hull coating
- a Wartsila air bubbler system.

The Inerta 160 coating appears to contribute significantly to the ice-transiting performance of the vessel. Analysis of the various database records from voyages and trials indicates that a dynamic coefficient of friction of about 0.03 exists between the coated hull and the ice. The presence of significant snow covers appear to increase the dynamic friction but to not more than double the above figure. The database contains no information concerning resistance without the Inerta coating and so no direct comparison can be made. However, most authorities regard a coefficient of 0.15 as being representative of normal hull-ice friction. Since resistance is directly related to friction, a coefficient of only one-fifth of a normal figure must clearly give the MV. Arctic a significant ice-transiting performance advantage.

The contribution of the Wartsila bubbler has proved to be more difficult to evaluate. The system consists of sixteen nozzles on either side discharging air at the bilge level over the length of the ship from the shoulder to the quarter regions. Various trials were conducted with and without the bubbler in operation.

The general conclusion is that the bubbler shows little advantage in the continuous-mode and actually appear to increase resistance when the ice thickness is above two-thirds of a metre. In the ramming-mode, some advantages are found but no more than can be achieved by a modest trim of the ship by the stern. Neither of these conclusions would provide adequate justification for the installation of the bubbler system. Such a conclusion, however, must take account of the fact that with its Inerta 160 coating, the MV. Arctic has a low friction coefficient and hence the scope for further improvement with a bubbler system is very limited.

Manoeuvering trials have shown a marked improvement in turning ability due to the bubbler as indicated in Attachment 4.11. The trend curve is based on two trials and has been drawn to delineate the probable least effect of the bubbler. The bubbler influence is apparently not one whereby the turning moment on the vessel, normally caused by rudder forces, is increased by the thrusting action of bubbling, but rather one in which the resisting ice is disturbed, weakened, or otherwise reduced in its resistive capability. This may be caused by simply blowing broken ice away or by causing the ice to break into smaller fragments (or indeed to break off from the parent ice by reducing buoyant support) and by lubricating the surrounding fragments of ice. It has been inferred from the results that in ice up to a certain thickness, the bubbler is capable of actually breaking ice, while beyond this it is only assisting with the removal of previously broken fragments, as indicated by the subsequent convergence of the diagram.

The above effects of the bubbler on ship turning in ice exceed expectations and seem to be greater than the effects of a thruster of comparable size. However, the question of justification would depend upon the ship's need for high manoeuverability. This matter was discussed in sub-section 4.4 where these needs are seen to be much less for a commercial vessel than for a dedicated icebreaker. For instance, the MV. Arctic logbook indicates that a course alteration exceeding 45° in ice occurs only about once per voyage and a full turn is rarely performed. Such a low level of demand would seriously affect the economics of installing a bubbler system. The justification would be much better in the case of a dedicated icebreaker which is called upon to perform a multitude of major manoeuvers daily.

4.7 Effect of power

The installed power of the MV Arctic is approximately 11.0 MW which, in combination with a shrouded propeller, provides a thrust equivalent to a power level of about 13.0 MW. The minimum power requirement for a CASPPR Class 2 vessel is approximately 4.2 MW and thus the power level installed in the MV. Arctic is equivalent to about three times the minimum requirement. It is interesting to note that this is about 50% above the minimum requirement for a Class 3 vessel.

In terms of continuous-mode performance, the rule minimum power requirement of 4.2 MW would be sufficient to permit the MV. Arctic to maintain slow progress (2 knots) in about 0.6m (2 feet) of ice. This is the generally accepted capability expected of a Class 2 vessel. The higher installed power increases this capability to 1.0 m of ice as has previously been shown in subsection 4.2.2. It has been noted, from the database, that the MV. Arctic has to utilise all of her available power in order to maintain progress at the ends of the season in Zone 13 of the Arctic which is her main operating region. Accordingly, it is concluded that the minimum CASPPR power requirements is inadequate for the operational requirements of this vessel, where the needs of a commercial service have to be fulfilled.

Similar conclusions can be reached with respect to operations in the ramming-mode. A comparison of the effects of different levels of power installed in the MV. Arctic is shown in Attachment 4.12. It is evident that the higher installed power at least doubles the MV. Arctic ramming-mode capability and again, there is a need for this in Zone 13 operations.

The above conclusions relate only to considerations of ice-transiting performance. Structural strength is also an important and inter-related consideration with respect to installed power and this matter is addressed in Section 6 of this report.

4.8 Model correlation

Ice resistance model tests were carried out in 1974 during the design period for the MV. Arctic. A predictor equation was developed from the model tests which provided a relationship between the following four parameters:

- ship resistance
- ship speed
- ice strength/thickness
- ice-friction.

The model test predictor equation developed for an ice strength of 690 kPa and friction of 0.15 is plotted in dimensionless form in Attachment 4.13. For comparison, the predictor equation developed from the full scale data of the MV. Arctic is also plotted for the same ice strength and friction. It can be seen that the two predictor lines intersect so that the model scale results either understates or overstates the resistance by a moderate amount depending upon the speed number. The overall result, however, would seem to conform to reasonable experimental expectations having regard to the early state-of-the-art of model ice testing as it existed ten years ago.

The above conclusion becomes less valid when the comparison is made with ice strength of 400 kPa and friction of 0.03 as was found to exist in the full-scale trials of the ship. The corresponding model and ship predictor lines are shown dotted in the diagram. The result is that there is not only a substantial shift downwards from the original set but, more significantly, the point of intersection is also shifted to the extreme left. This means that the model results overstate the resistance throughout by an amount which increases progressively with speed number and thus over-emphasises the speed sensitivity. It must be pointed out, however, that at the intersection point, corresponding to near zero speed, the ice thickness would be 1 metre which is close to the upper limit of the MV. Arctic's continuous-mode capability as concluded in sub-section 4.2.

The fact that the model results predicted a continuous-mode ice capability of 2 feet (0.6m) rather than 3 feet (1 m) emphasises the importance to be attached to the choice of ice strength and friction values used for prediction purposes. In 1974, it was not known that a low friction coating was to be used on the ship, although some model tests were performed at that friction value. The question of overpredicted speed sensitivity may be due to a number of factors including the process of regression applied to the model test results.

The conclusion that can be drawn is that it is possible to achieve the desirable one-to-one objective for model/full scale correlation. Continual improvements to model-testing, equipment, materials and procedures all contribute to this objective. Accuracy of prediction, however, is highly dependent upon such factors as friction and ice strength, as the fore-going has demonstrated. Accordingly, this reinforces the need to state ice strength, thickness, etc. when determining power requirements and, should be included in the CASPPR criteria for propulsion as stated in Section 5 of this report.

4.9 Summary of findings

A number of important conclusions are reached from the analysis of the 1979-81 database concerning the ice-transiting performance of the MV. Arctic. The principal findings are as follows:

a) The continuous-mode capability of the MV. Arctic is such that a creep speed of advance can be maintained in level ice of one metre thick. This capability far exceeds the normal expectations of a Class 2 vessel.

b) The ramming-mode capability of the MV. Arctic is predicted to reach an upper limit in about 3.5 metres thickness of level ice. A comparable ridge-penetrating capability has been established for the vessel depending upon field ice and ridge dimensions.

c) The ramming strategy which results in the optimum speed of advance and fuel economy has been established for the MV. Arctic in various ice thicknesses. The impact speed varies, from about 7 knots (3.5 m/sec) in 1 metre level ice down to about 3 knots (1.5 m/sec) in 3.5 metre ice, for optimum speed of advance.

d) The manoeuvering capabilities of the MV. Arctic reveal good directional but only moderate turning qualities in ice. As a collision avoidance tactic, stopping is more effective than turning the ship in ice of more than a modest thickness.

e) The ice-transiting qualities of the MV. Arctic have been found to be sensitive to changes in hull geometry resulting from the effects of trim and heel. In particular, changes which produce increased flare angles along the waterline region appear to improve the ship's performance in ice.

f) The special hull coating applied to the MV. Arctic is found to reduce hull/ice friction to about one-fifth of the normal value. The net result is about 30% reduction in resistance which translates into a comparable increase in ice-transiting performance.

g) The air bubbler system installed on the MV. Arctic produces no detectable improvement in continuous or ramming-mode performance. This is probably due to the low friction level already achieved by the special hull coating. However, in manoeuvering, the bubbler noticeably improves the turning qualities of the ship probably due to effects which tend to enhance the breaking and clearing of the ice cover.

h) The propulsive power level installed on the MV. Arctic, whilst being about three times the minimum power requirement for her class, is found to be necessary to meet substantially all of the service demands encountered during her arctic operations.

i) The results obtained from the early model tests of the MV. Arctic provide the means of accurately predicting the upper limit of continuous-mode capability in level ice. The effect of speed on total resistance, however, is found to be overstated by the model-scale predictor.

This completes the main findings on ice-transiting performance, except as they may impact on the provisions of CASPPR. In that regard, the following conclusions are offered for consideration.

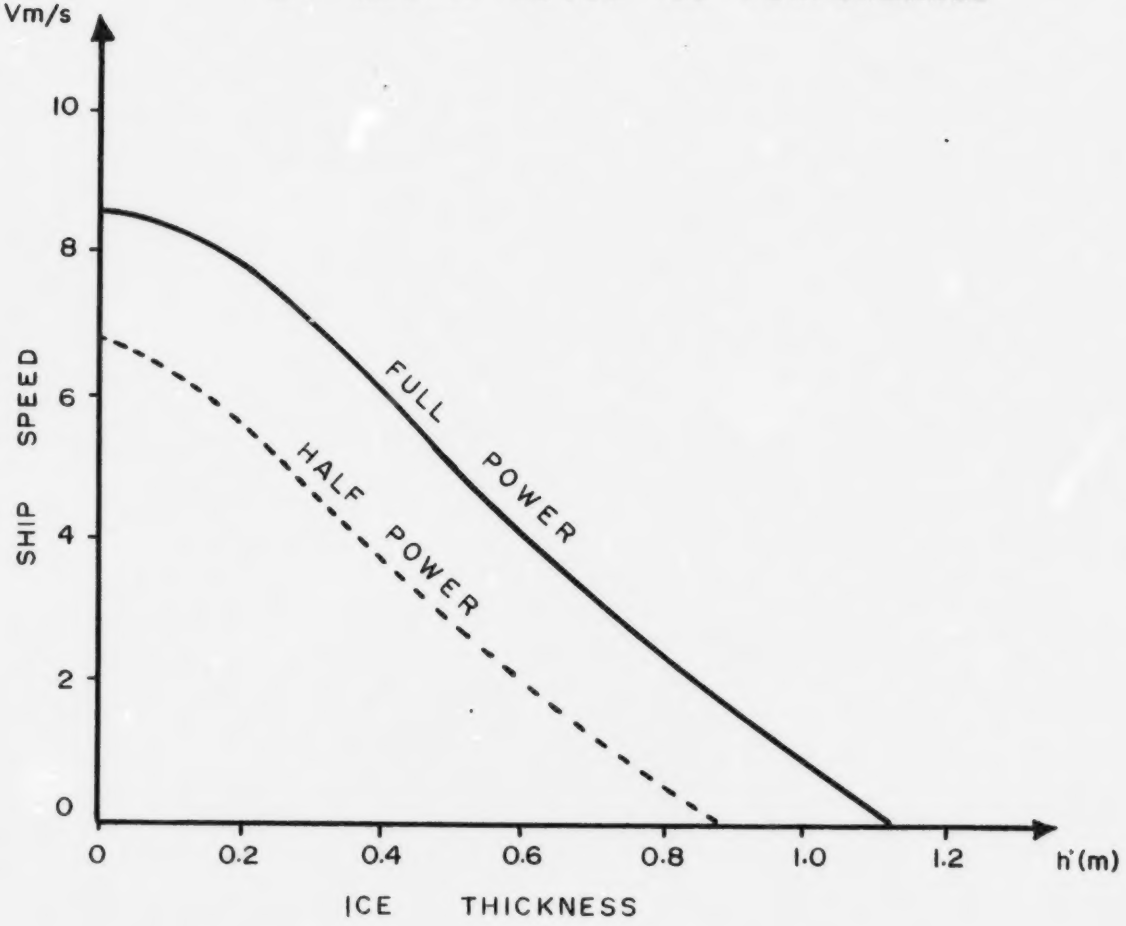
- The CASPPR minimum power requirements are found to be inadequate for the commercial missions of the MV. Arctic in that they greatly understate the ice-transiting needs of an Ice Class 2 vessel operating in the specified zones and seasons of the arctic.
- The ice-transiting requirements for ice-class vessels should be identified in terms of a minimum speed in ice relationship.

- The manoeuvering requirements for ice-class vessels should be identified in terms of turning radius or turning moment at low ice speeds. Such considerations should also embrace directional stability for good course-keeping in ice.
- The strength requirements of rudders and steering gears should be stated more explicitly.

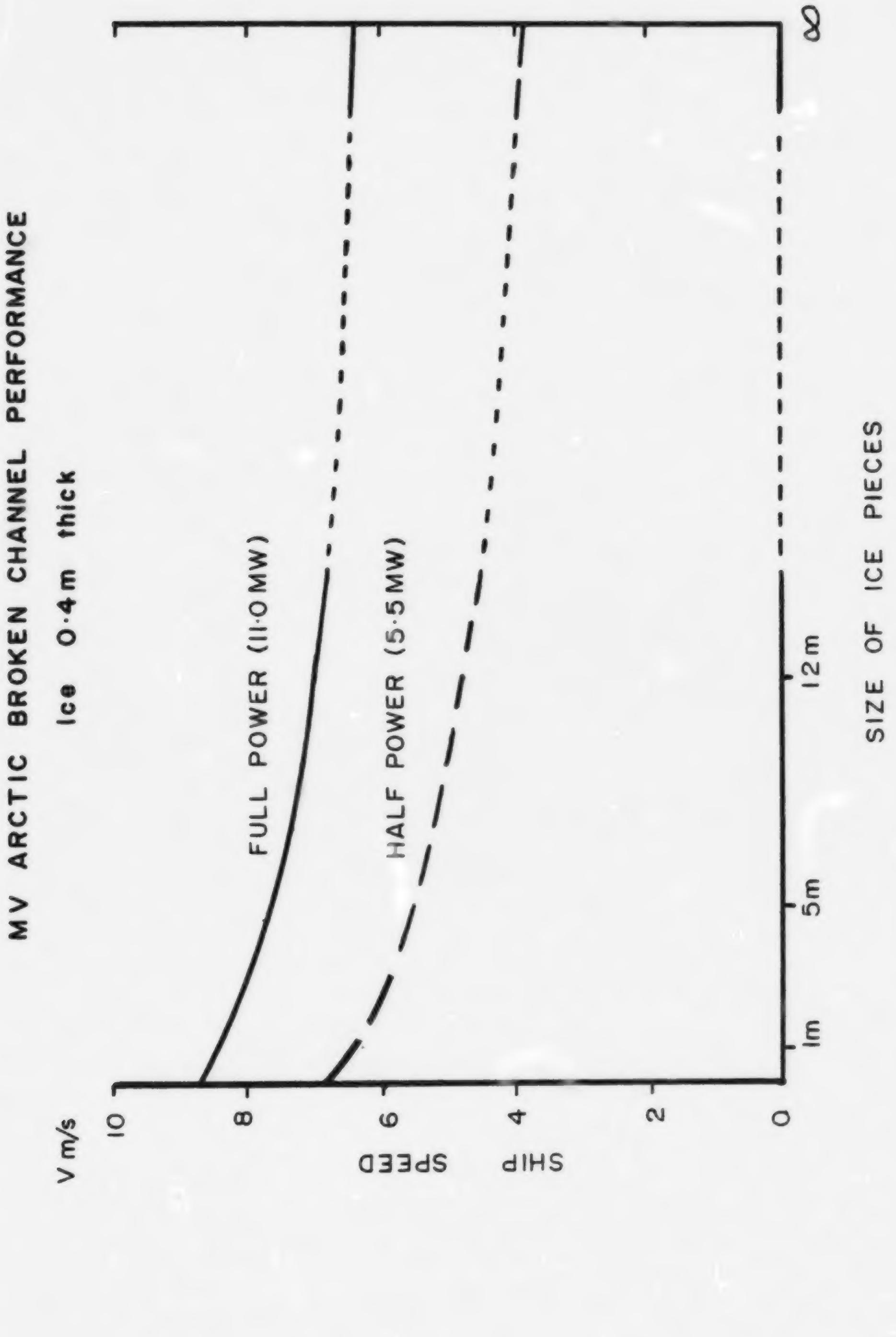
In addition to the above, the provisions of CASPPR should incorporate a relationship between ice-transiting capabilities (particulary ramming and manoeuvering) and structural strength of the hull to ensure compatibility of the total design.

ATTACHMENT 4.1

MV ARCTIC LEVEL ICE PERFORMANCE



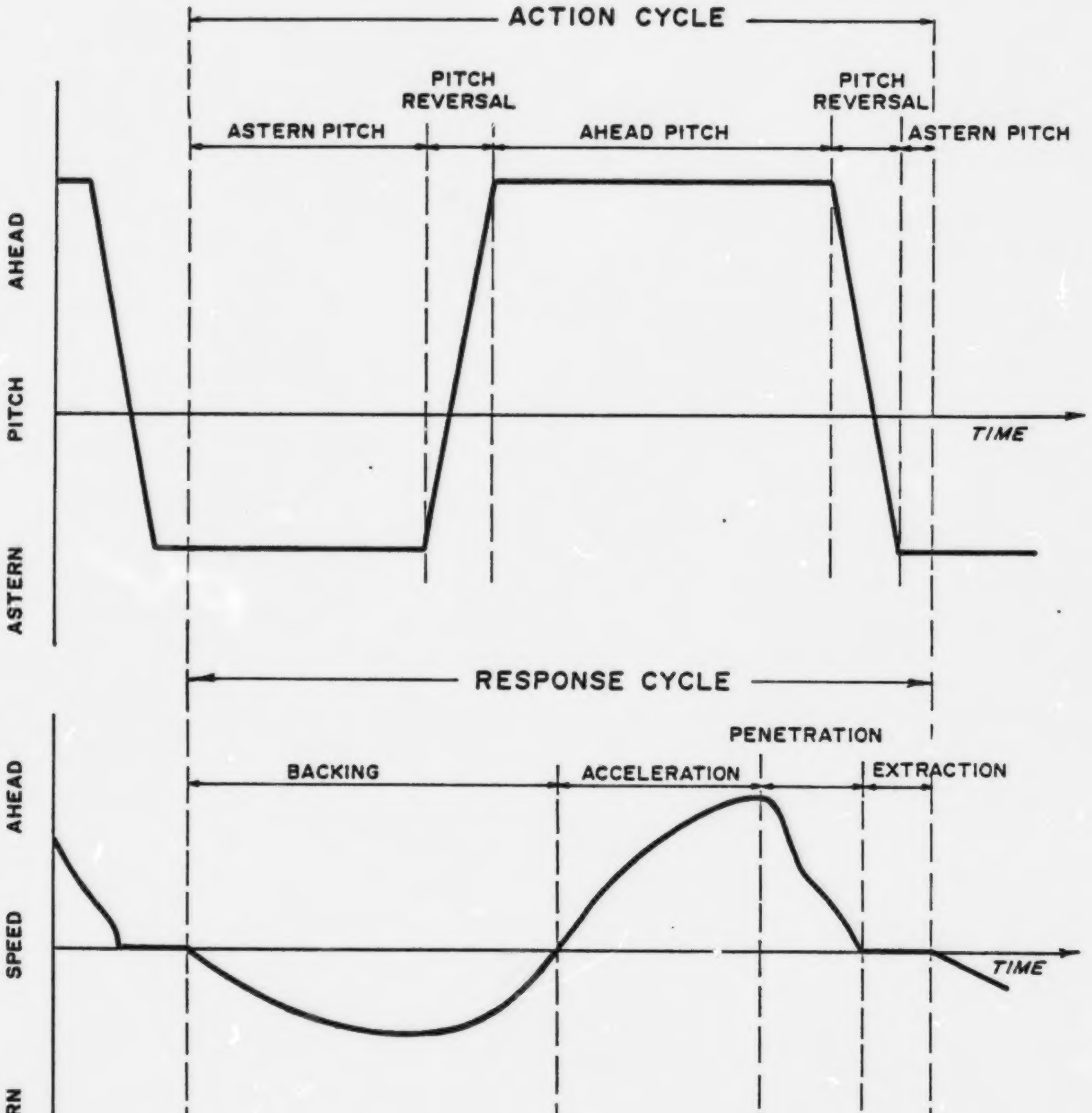
ATTACHMENT 4.2



MV ARCTIC BROKEN CHANNEL PERFORMANCE

Ice 0·4m thick

IDEALIZED RAMMING CYCLE AND COMPONENTS



TYPICAL EXAMPLES of EXTENDED REVERSAL DURATION

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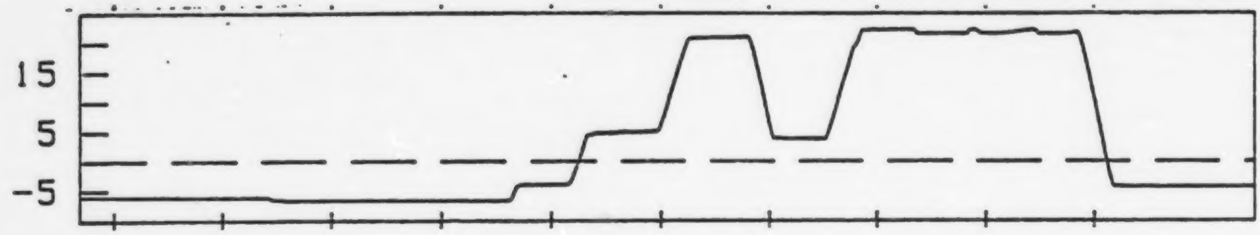
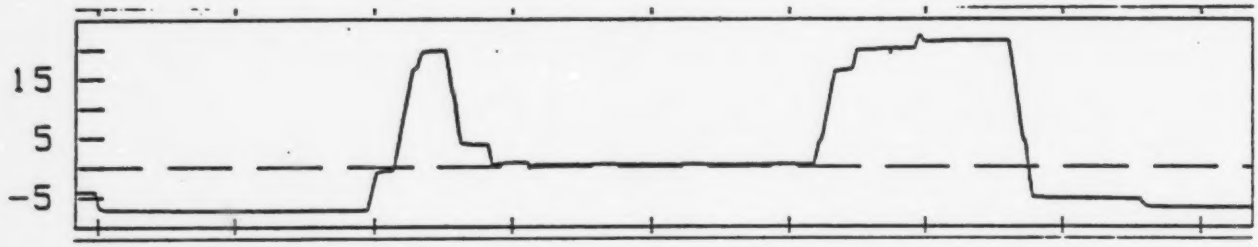
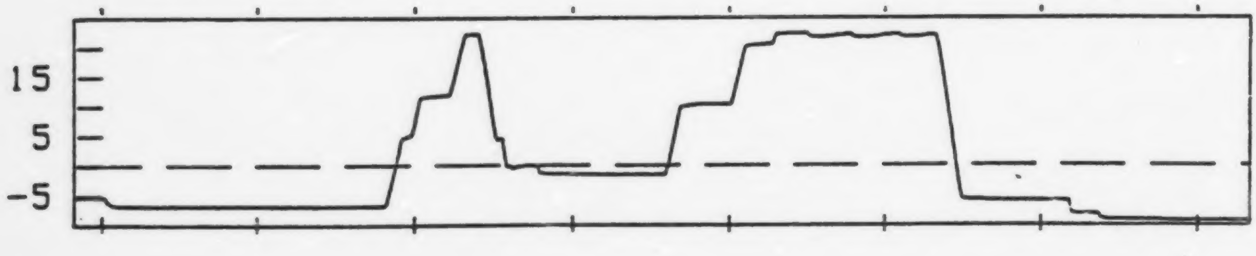


RAM No A8

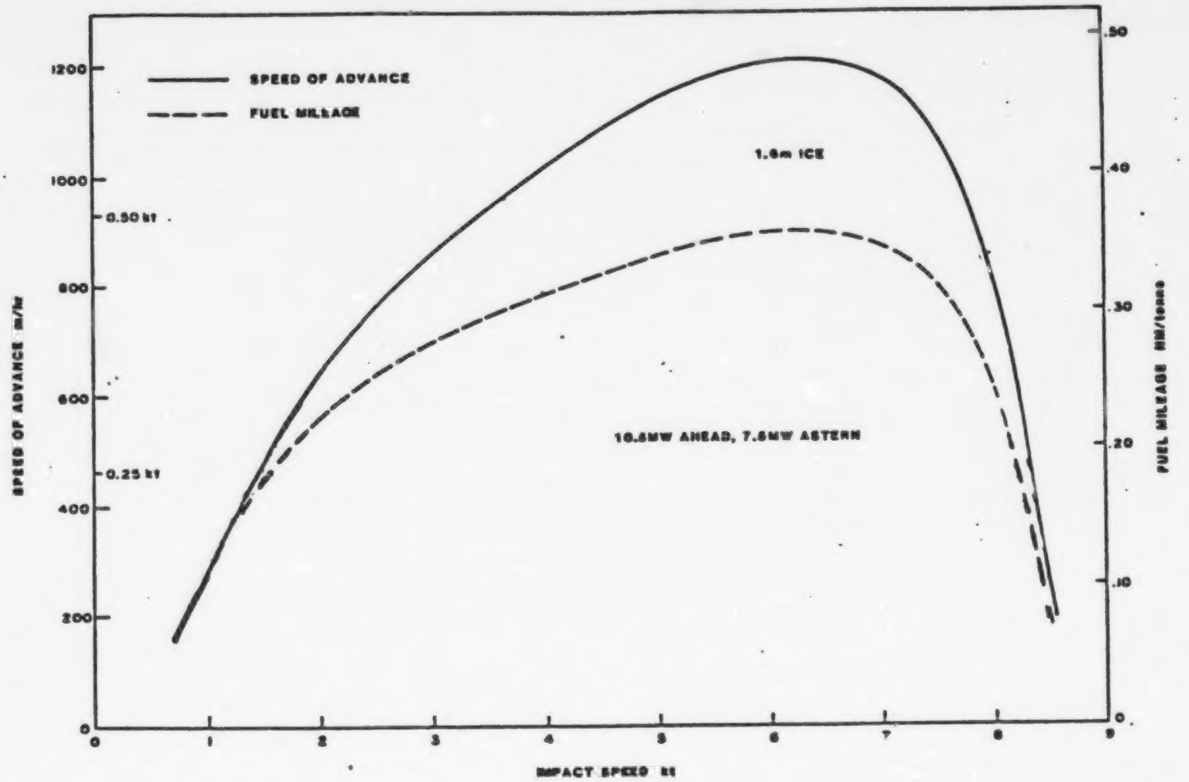


RAM No A9

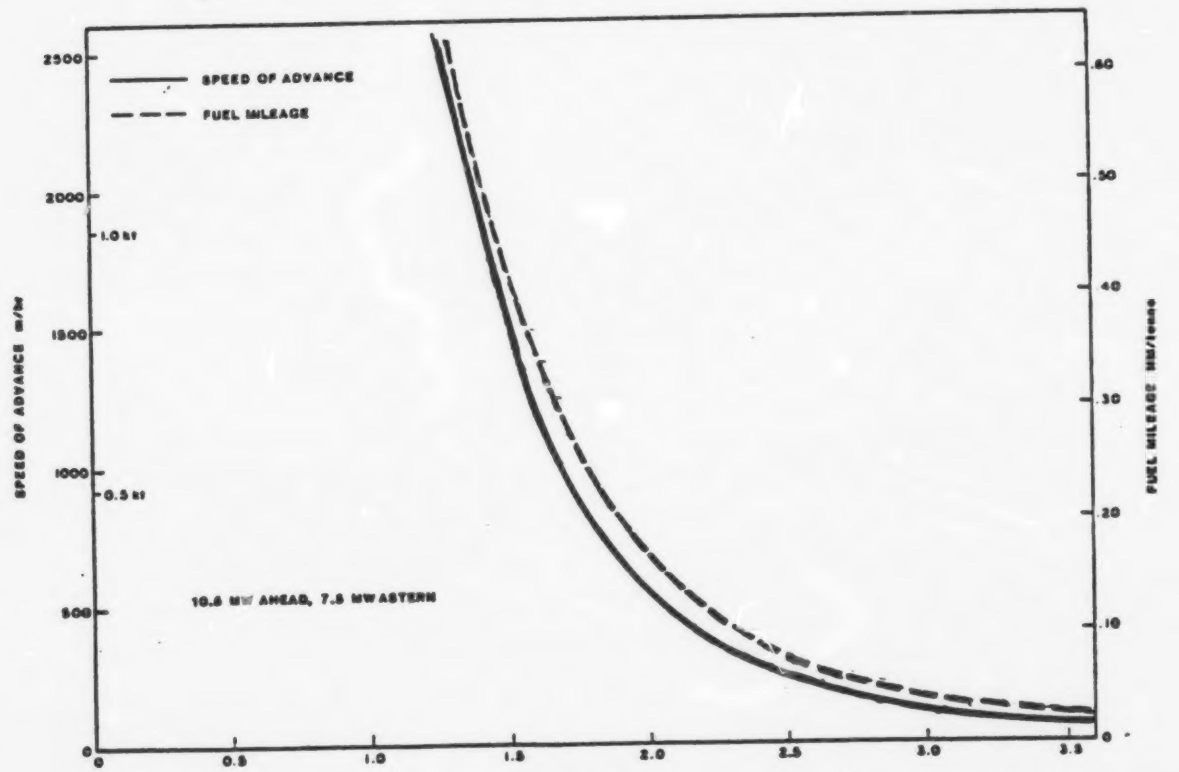


ATTACHMENT 4.5

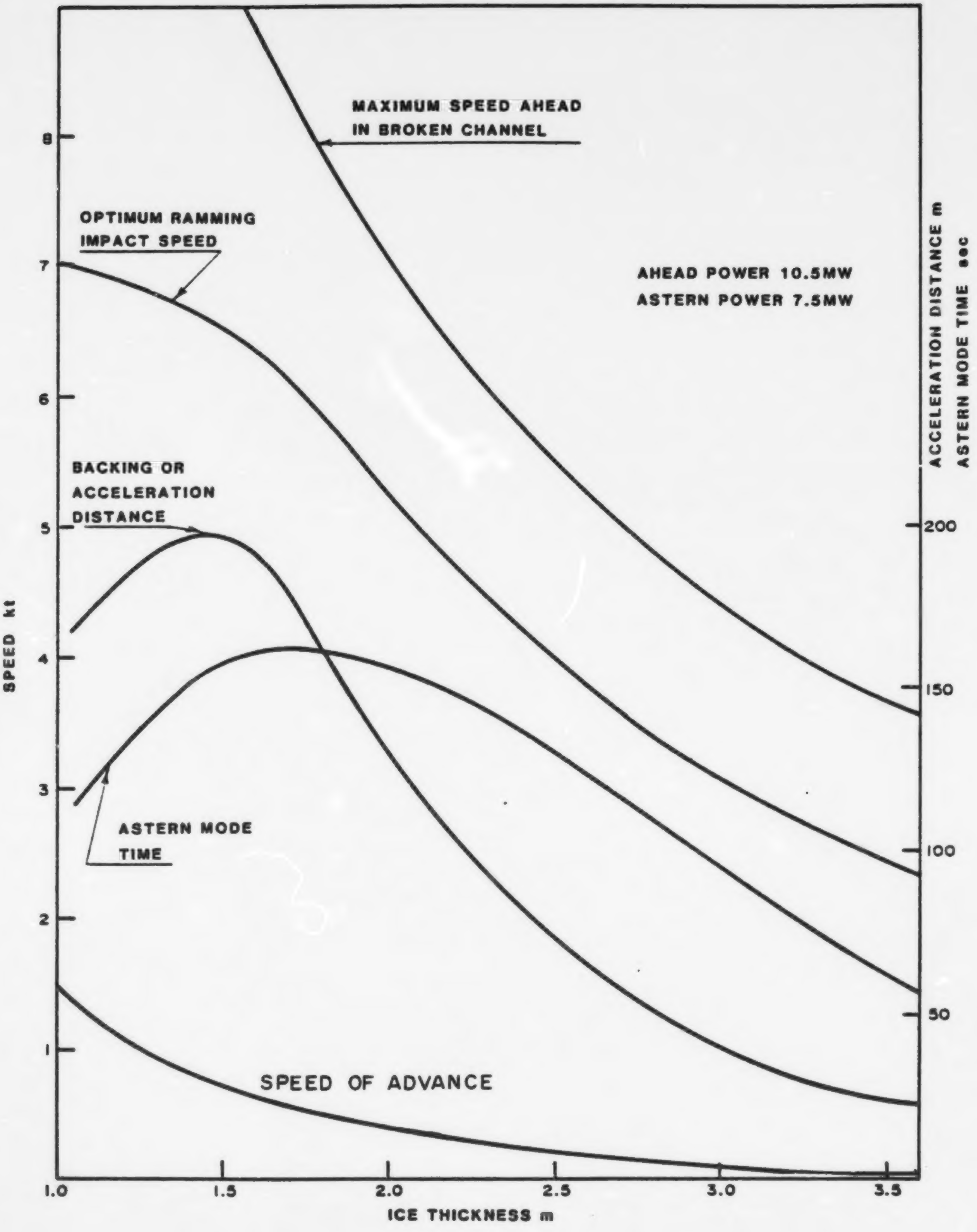
a SPEED OF ADVANCE AND FUEL MILEAGE VERSUS IMPACT SPEED



b OPTIMUM SPEED OF ADVANCE AND FUEL MILEAGE VERSUS ICE THICKNESS

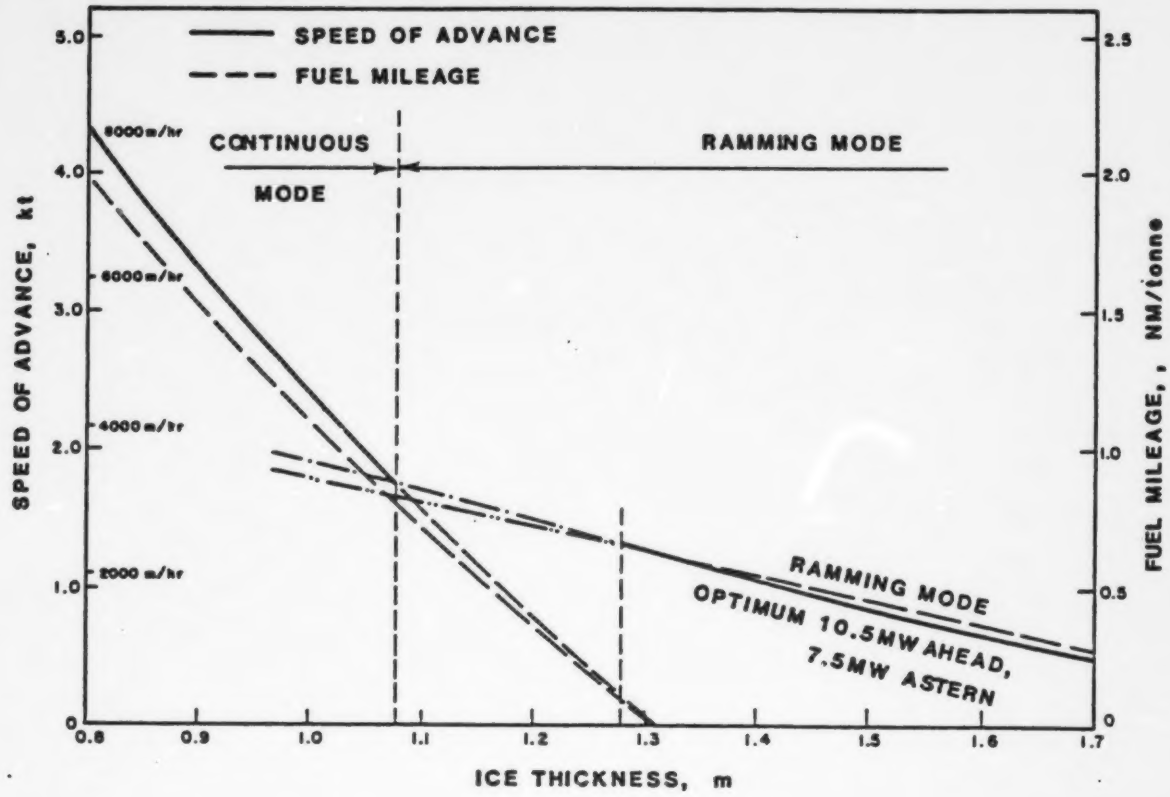


RAMMING STRATEGY

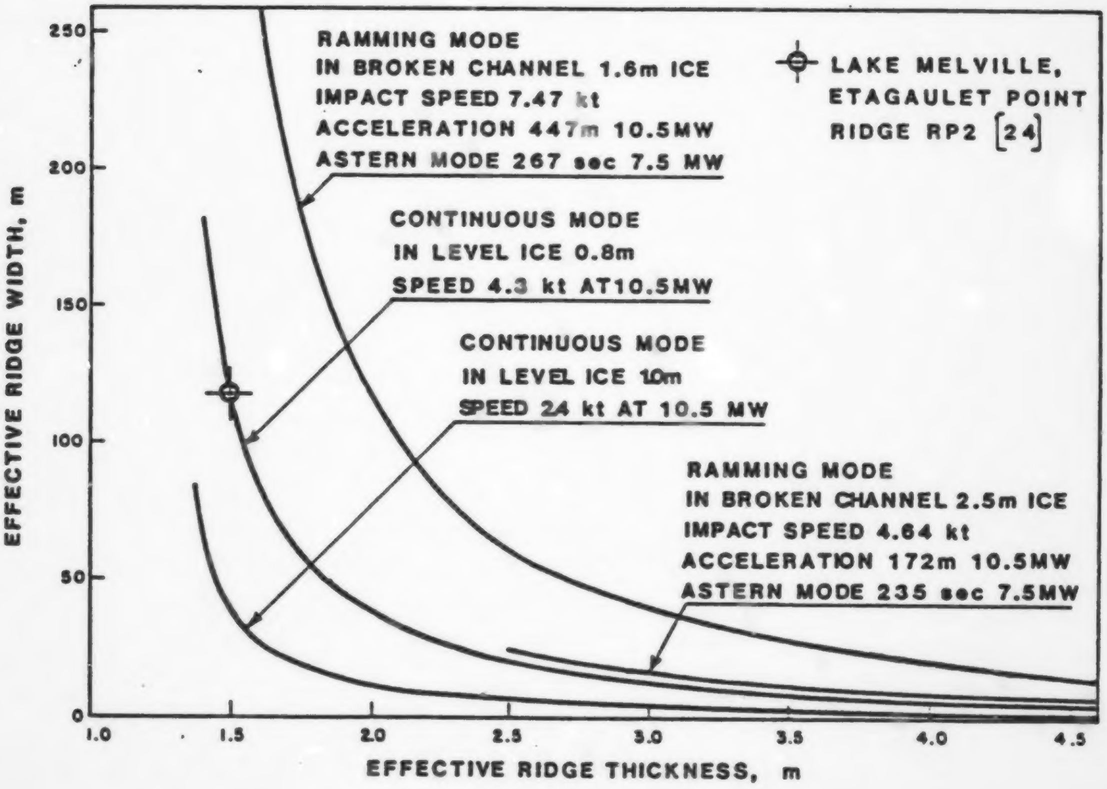


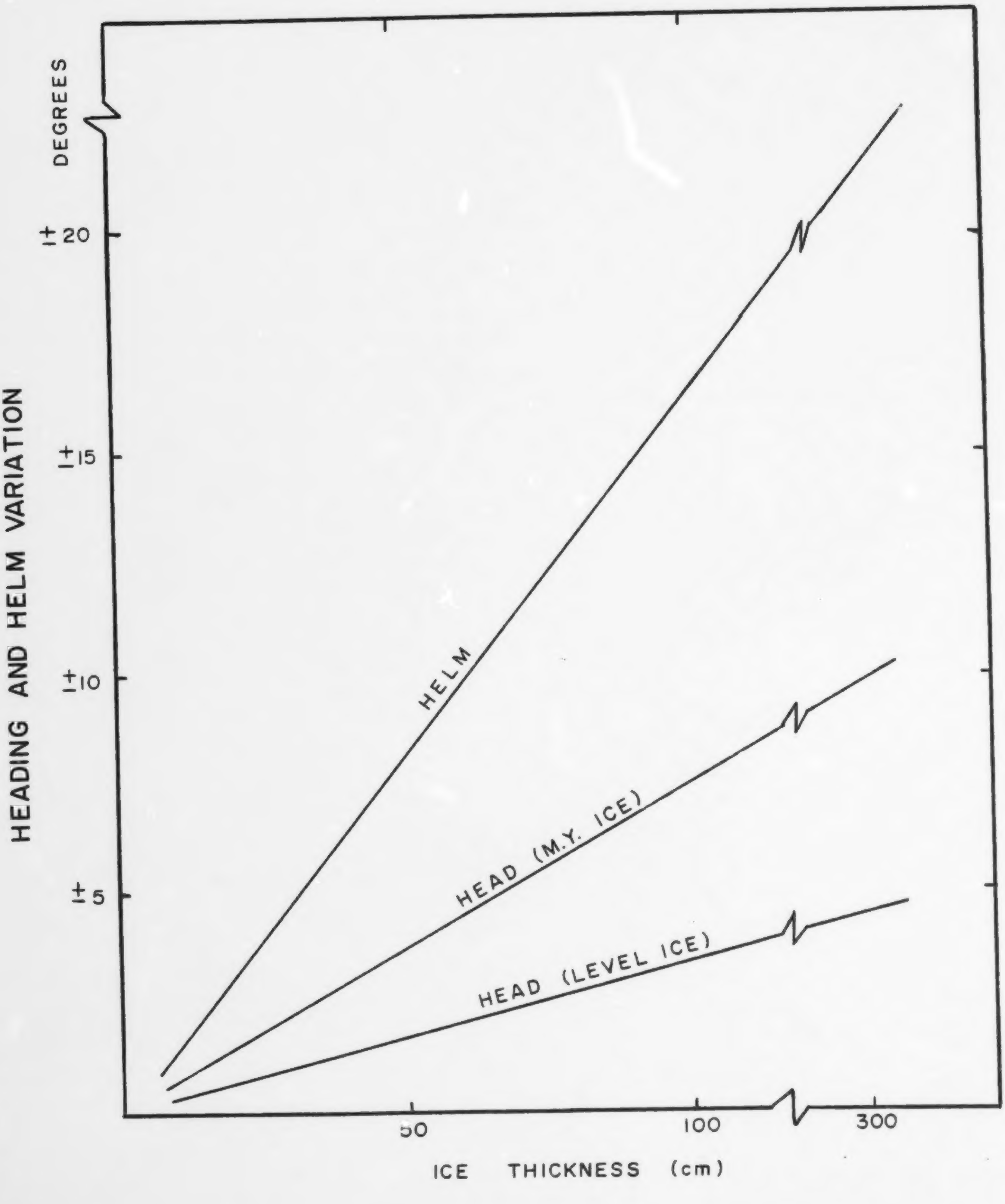
ATTACHMENT 4.7

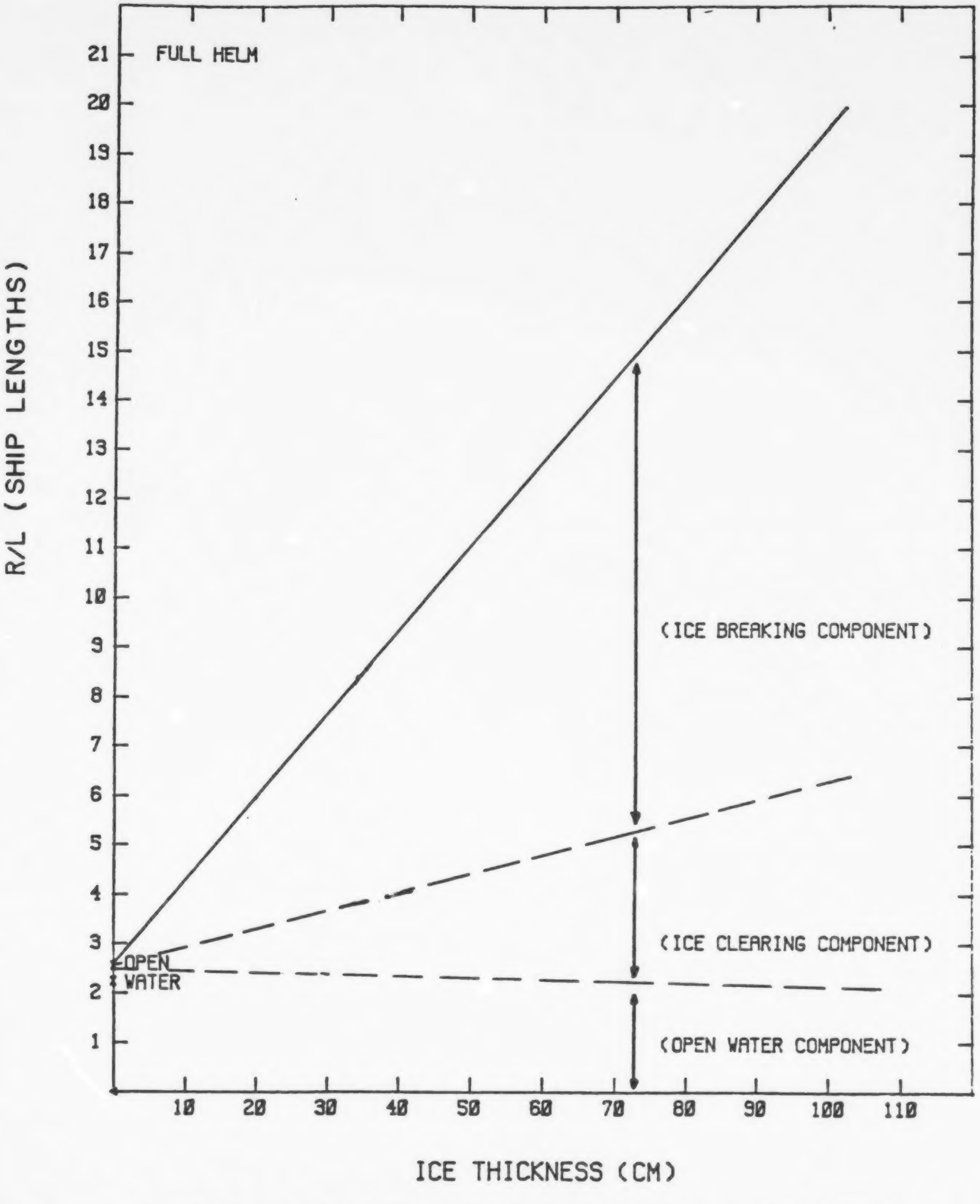
a TRANSITION CONTINUOUS RAMMING MODE



b RIDGE BREACHING CAPABILITIES

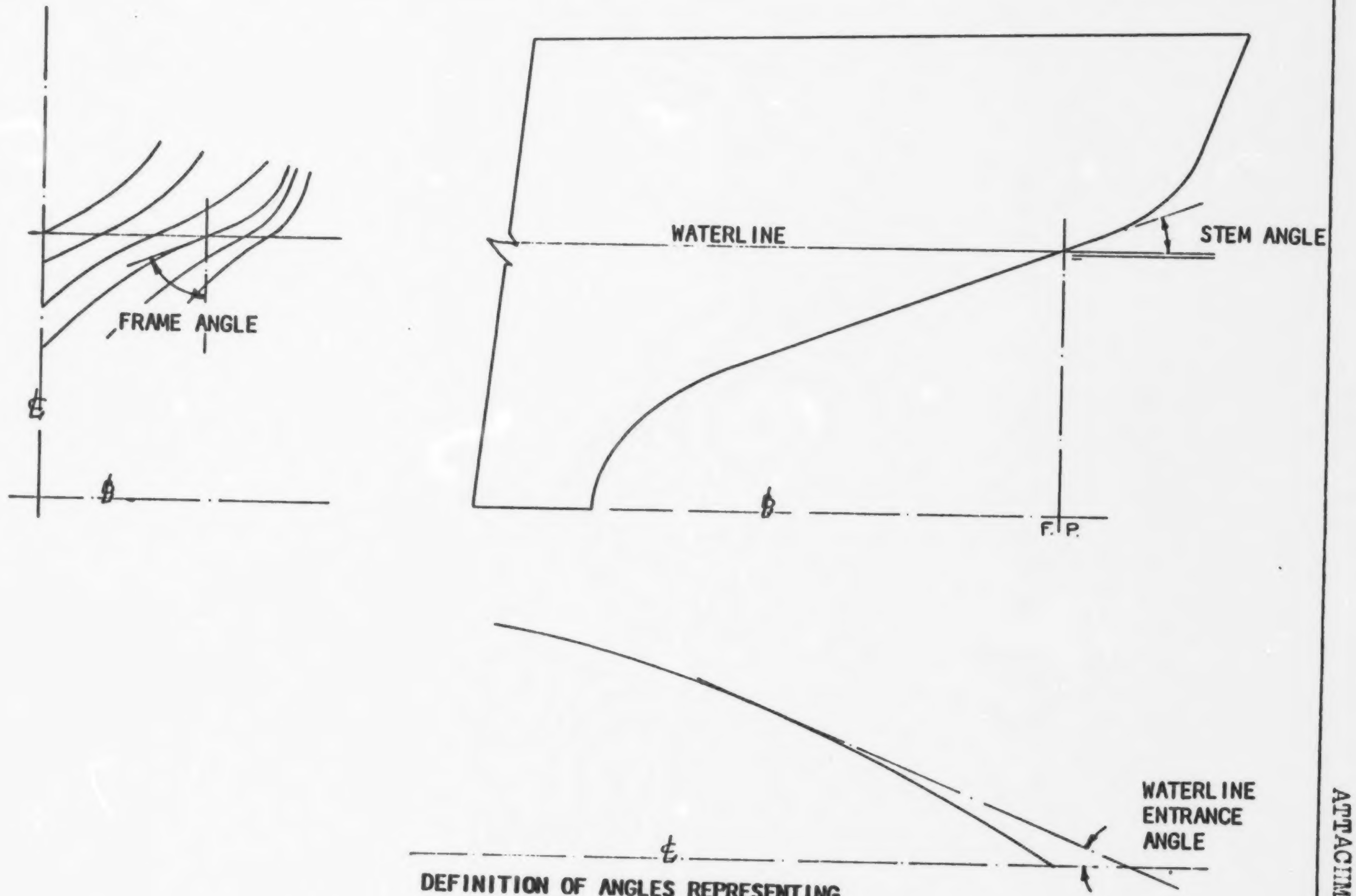



HEADING AND HELM VARIATION
DEGREES
±20
±15
±10
±5
HELM
HEAD (M.Y. ICE)
HEAD (LEVEL ICE)
50
100
300
ICE THICKNESS (cm)

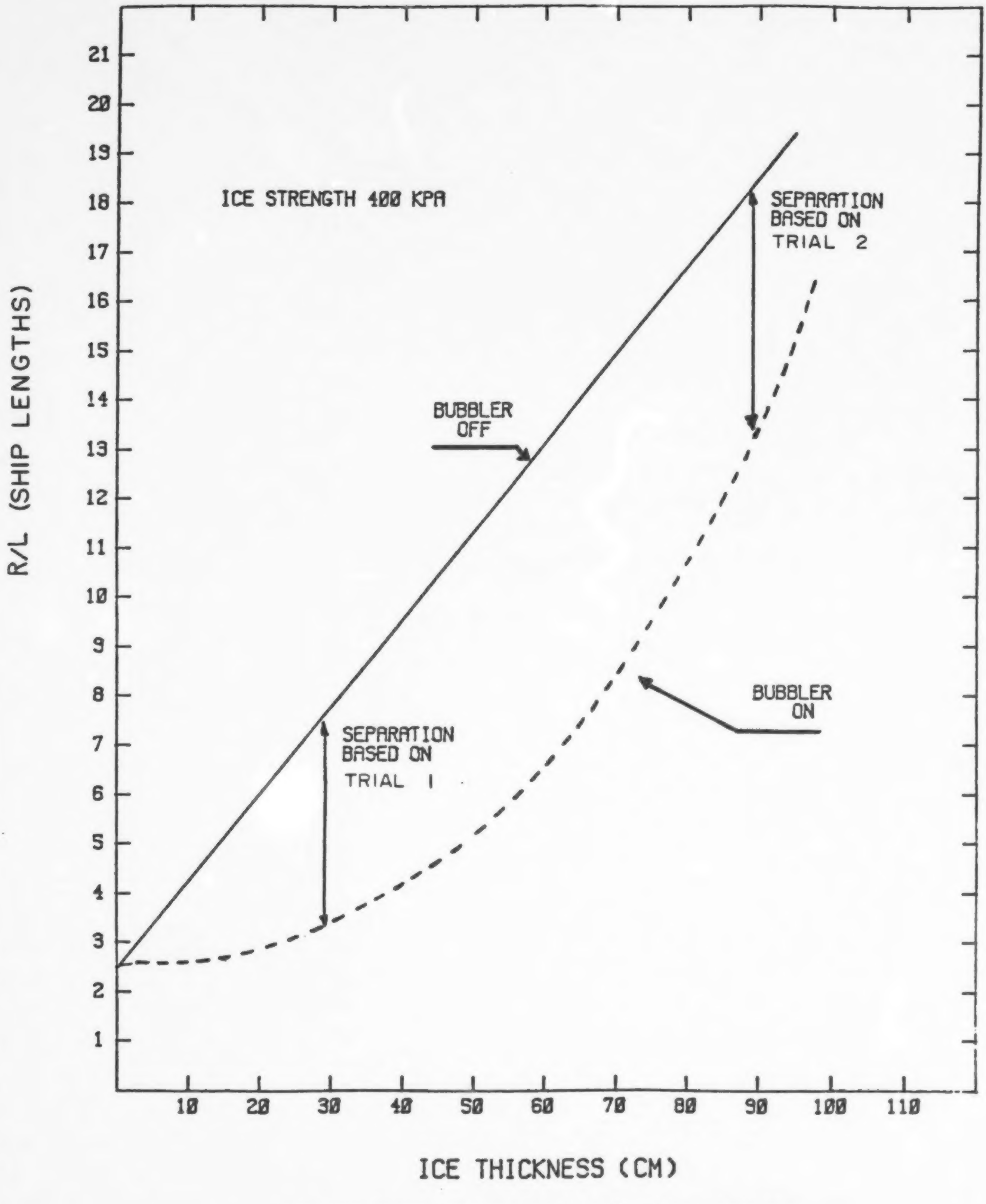


STEADY TURN RADIUS UNDER VARIOUS CONDITIONS

ATTACHMENT 4.10



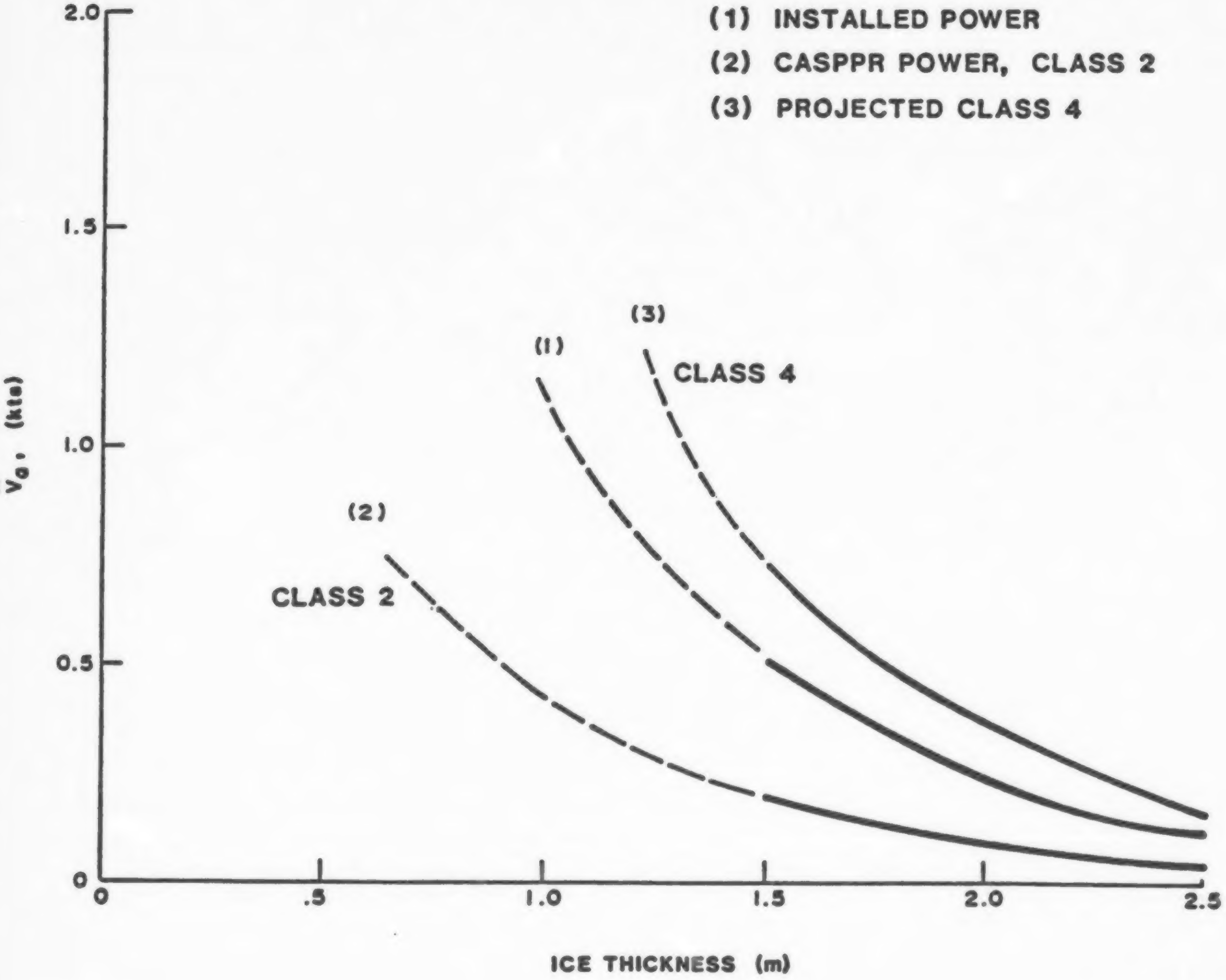
DEFINITION OF ANGLES REPRESENTING
BOW GEOMETRY



EFFECT OF BUBBLER (AT FULL HELM)

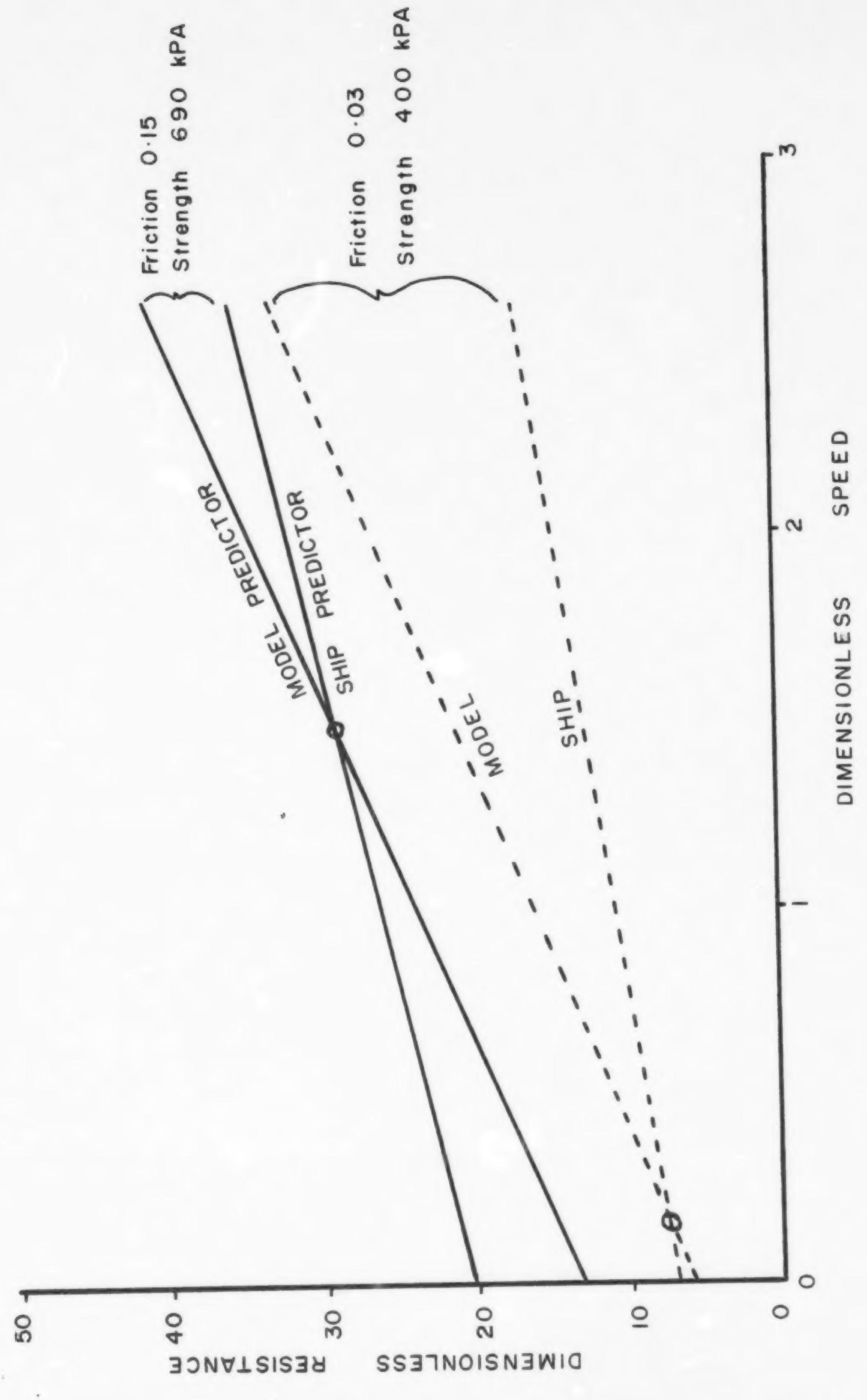
ATTACHMENT 4.12

COMPARISON OF THE EFFECTS OF INSTALLED VERSUS CASPPR LEVELS



ATTACHMENT 4.13

DIMENSIONLESS RESISTANCE VERSUS DIMENSIONLESS SPEED



SECTION 5

PROPULSIVE PERFORMANCE

5.1 Introduction

The propulsion system of the MV. Arctic comprises a medium speed diesel engine coupled through a single reduction gear to a controllable pitch (c.p.) propeller working in a nozzle. A schematic arrangement of the propulsion system is given in Attachment 5.1. The principal particulars are provided in Attachment 5.2.

The system is controlled through a combinator which provides overload and overtorque protection in conjunction with the engine governor by inter-relating power, speed, and propeller pitch in a pre-programmed manner. Evidence of the effectiveness of this important safety device when operating in ice is provided later.

The vessel is equipped with a c.p. propeller. The propeller operates in a nozzle, the effect of which is to boost the thrust by about 70% when developing full power in the bollard or ship-stationary condition.

All of the above describes a propulsion system which in operation is designed to be uncomplicated, effective, economical, and safe. These qualities are demonstrated in the results obtained from the 1979-1981 data collection and analysis program. The objective of the data analysis activity was to determine the effect of ice-ingestion on the performance and strength of the main machinery, gear train, shafting, and propeller of the MV. Arctic. The results are summarized in this section of this report.

5.2 Propulsion signatures

In order to obtain an understanding of the nature and extent of loads experienced by the propulsion system, signatures of shaft torque and propeller thrust were developed from the database for the following spectrum of operating conditions:

- open water (smooth and rough)
- broken channel (behind icebreakers)
- level ice (continuous mode)
- level ice (ramming mode)
- ridged ice (ramming ice)

The response of the system in open water is taken as a baseline and typical examples of this are provided in Attachment 5.3 for smooth and rough seastate conditions. Neglecting the long period undulations due to ship motion in the rough seastate, it will be seen that both signatures exhibit torque and thrust amplitudes varying 10-15% about the mean values and occurring at about 10 cycles per second corresponding to the blade passing frequency. When the vessel operates in ice affected waters, similar signatures occur but interspersed at varying intervals by torque and thrust spikes due to ice interaction with the propeller. Three main categories of interaction events occur as shown in Attachment 5.4, and are described as follows,

Case A: positive excursion of torque as a discrete spike with no obvious change of thrust;

Case B: positive excursion of torque with side bands associated with a positive and negative change of thrust;

Case C: positive excursion of torque with side bands associated with a large negative excursion of thrust.

The total time of the events do not exceed 1 to 5 seconds. All events are characterized by a well defined peak and this is believed to be indicative of a single blade impact with an ice block which destroys the block and the side bands are due to impact of the blades with the fragments.

It is of interest to note that some excursions of shaft thrust are initially positive while others are initially negative. All excursions of torque which can be attributable to impact with ice are positive. It is also noted that the initial excursion of propeller thrust leads the corresponding excursion of torque in most of the events identified. It is not possible to account for either positive or negative excursions of thrust in hydrodynamic terms without simultaneous and complementary positive or negative change in torque. Therefore, it has been concluded that the excursions of thrust which are not accompanied by a simultaneous and similar change of torque, are due to mechanical effects of ice impact upon the propeller disc.

It is believed to be reasonable that the shaft thrust or axial load should decrease if the vessel proceeds ahead with ahead thrust and the propeller impacts an ice block on the forward face. Similarly, if the vessel is moving astern using astern pitch, the astern thrust will momentarily decrease if ice bears upon the aft face of the propeller. If, however, the vessel is moving astern when the propeller pitch is in the ahead position, and an ice block impinges upon the aft face of the propeller, the ahead thrust will initially increase. This type of operation and incident is typical when the vessel is ramming and gives rise to the largest thrust and torque excursions.

5.3 Significance of ice torques and thrusts

Torque and thrust excursions occur under all operating conditions but it is only those exceeding a certain magnitude which will be of significance in their effect on the propulsion system. Accordingly, it is necessary to establish a "significance level" against which actual propulsion load excursions can be compared and evaluated. An appropriate baseline is the mean value of torque and thrust developed on the shaft at the maximum continuous rating (MCR) of the engine. The corresponding MCR values for the MV. Arctic are as follows:

MCR Torque = 725 kNm

MCR Thrust = 875 kN

Various factors of safety are adopted in the design and sizing of the propulsion train but the criterion of most relevence in this vessel is the ice torque provision of CASPPR which amounts to 490 kNm or 67% MCR torque for the MV. Arctic. Accordingly, this investigation has adopted the following level as the test of significance of actual data recorded.

Upper Significant Peak Torque = 1.67 MCR Torque

The above applies only to transient torque excursions (spikes) since the diesel engine would stall if subjected to a sustained ice torque of such magnitude. The database has confirmed that the torque excursions are transient with very rapid rise and decay times. The records contain no evidence of stalling resulting from the creation of a sustained overtorque due to an ice jam in the propeller.

It was stated earlier that the major transient overtorques occur during the ramming mode of operation. A typical record covering 45 minutes of ramming in level ice is provided in Attachment 5.5 with the engine operated at MCR conditions. It is evident that although some large ice torques occur, they are still comfortably below the 1.67 MCR significance level. If a similar significance is adopted for thrust, the attachment also reveals a lower level of actual thrust excursions.

It can not be concluded, however, that all recorded overtorques lie within the above ice torque design provisions. There is evidence from the database that the actual overtorques, in a few instances, rise as high as twice the mean torque and by extrapolation to full power conditions could reach the 2 MCR level. The upper boundary of overtorques are shown in Attachment 5.6 for the five categories of ship operating conditions. The region of particular significance is the shaded area above the 1.67 MCR level, where there is a possibility that the transient overtorques can exceed the CASPPR design provisions when the engine is at full power. No actual events of this magnitude have been recorded over 46 hours of data gathering time and hence the frequency of such occurrences appears to be very low. The shaded area encompasses only two of the operating modes, namely, ramming and broken channel operations. The latter is usually performed at reduced power and hence may not be of significance. Ramming operations may, however, utilise full power and hence the possiblity of design overtorque exceedence is greatest in this operating category. Similar effects can be seen in Attachment 5.7 with respect to thrust.

On the assumption that overloads can attain the 2 MCR level, even though infrequently, it is appropriate now to address the matter of protection through system control and the question of propulsion train strength.

5.4 System control and protection

The combined action of the combinator and governor was described earlier (see Section 5.1) and reference was made to its effectiveness as a safety device.

An example of the operation of the protection system when ice is ingested into the propeller is provided in Attachment 5.8. It can be seen in the Attachment that the engine was operating at full power, fuel rack at the maximum setting, at approximately 22.5° pitch, 143 r.p.m. shaft speed. As ice was ingested, shaft speed decreased and torque increased but, as the fuel rack was at the maximum setting, to maintain set speed and prevent overtorquing the pitch reduced automatically. After the r.p.m. reverted to its set value, the pitch control and the engine governor automatically adjusted the fuel rack to maintain constant engine speed. From the Attachment it may be seen that the time for the system to respond to the reduction of engine speed brought about from an increase in torque is approximately 2 seconds. Propeller pitch was shed which allowed the engine speed to increase to the set position when the reduction of pitch ceased. The dwell period at reduced pitch was 10 seconds when pitch as reapplied to the set value over 11 seconds. The response of the engine fuel rack is according to governor demand and is extremely rapid. It maybe seen that the fuel rack follows pitch and responds to engine speed. No relationship can be estimated between these events and ship speed as the periods are extremely small and have no detectable influence on the vessel's momentum.

5.5 Propeller considerations

The propeller is the recipient of all ice interaction events and, consequently, its strength must be a major consideration. The pitch shedding action of the control system described previously whilst preventing sustained overloads nevertheless does not soften the instantaneous effect of the initial ice impact tending to damage, bend or break the propeller blades. The data acquisition system fitted to the MV. Arctic was not designed to address the strength considerations of the propeller and, accordingly, an analytical rather than empirical approach was pursued. This adopted the criteria of 2 MCR torque and thrust interaction events as the basis for the investigation, with the ice impacting at various radial distances along the propeller blade. The results indicate that even with ice impact near the blade tip, the resultant root bending stress does not exceed the yield strength of the blade material. The fact that no propeller damage has occurred on the MV. Arctic seems to confirm the above theoretical conclusion.

5.6 Shaft consideration

An investigation was undertaken to examine the probable fatigue effect on the shafting due to the impact loads (torque and thrust spikes) recorded during ice operations. Based upon a maximum of 60 ice-transiting days per year accumulated over 5 arctic voyages, the following load reversals are anticipated during a 15 year life-cycle of the MV. Arctic.

Significance level	Estimated Frequency	Ship Life
Exceedence of 1.3 MCR	10 per hour	2×10^5 cycles
Exceedence of 1.67 MCR	10 per voyage	max. 10^3 cycles

In order to provide for an ample margin of error in the above estimates, a lifetime expectancy of 10^7 cycles was used for the following fatigue effect comparisons based on 2 MCR level imposed on the smaller diameter intermediate shaft.

Loading condition	Shaft Stress at 2 MCR	Fatigue Stress at 10^7 cycles	Factor Safety
Torsional	50 MPa	150 MPa	3
Axial	10 MPa	200 MPa	20

It appears evident from the above that fatigue failure of the shafting is not a consideration even with transient loads of 2 MCR, which exceed the 1.67 MCR design criterion provided for in CASPPR.

Bending effects must also be taken into consideration, however, and the propeller shaft must not only be dimensioned to transmit torque and thrust, but also to support the overhung weight of the propeller. The shaft must also withstand the effects of the various dynamic forces due to eccentric thrust and transverse forces produced by the propeller blade operating in an irregular wake. The bending stresses in the propeller shaft due to the overhung weight of the propeller are estimated to be of the order of 20 MPa but can be increased by a factor of 3 when the vessel is operating in rough weather, and possibly an even larger factor may apply when the propeller blades strike ice blocks.

No measurements have been taken to investigate the bending stresses in the propeller shaft when ice impacts the blade. It is probable that there are considerable vertical and transverse forces generated under these conditions. These forces can be felt as hull girder vibrations due to the propeller shaft hammering in the aft stern-tube bearing when ice is ingested by the propeller. As there have been no reports of damage to the propeller bearings and shaft seals, it is difficult to comment on whether shaft bending may produce problems in the longer term.

5.7 Gearing considerations

The effects of torque and thrust variations on the propeller are transmitted to the gears through the propeller shaft. Provided the variations to be expected are specified to the gear manufacturer at the design stage, they can be accommodated. The gears fitted to the MV Arctic comply with CASPPR requirements and have been specified to be suitable for continuous transmission of 30% in excess of the rated torque of the engine. Without considerably more information on the type of loading and service the gears will experience, the single criteria of "make the gear bigger by increasing the rated value of torque" only addresses the allowable design stress of the gear teeth. The dynamic stresses which are imposed upon the system when vessels operate in ice covered waters, are not addressed by the Regulations and the most important allowances to be used in the design are therefore at the gear maker's discretion. It is probable, however, that the application of various overload and other factors of safety will bring the maker's overall design criterion to a value greater than 2 MCR torque of the engine. Transient torques of about 2 MCR would, therefore, be accommodated. This is borne out by the fact that, to date, no gearing problems have been reported.

An area of potential concern, however, arises from the fact that the thrust block is integral with the gear casing as shown in Attachment 5.9. The gear casing will be subject to deformation under the full range of thrust actions, transients and reversals, which may affect the internal alignment of the gearing and eventually lead to problems. It would seem advisable, therefore, to separate the thrust block and thus eliminate the risk of transmitting axial loads into the gears.

5.8 Techno-economic considerations

A life-cycle cost comparision has been made between the as-fitted medium speed diesel/c.p. propeller/nozzle propulsion system of the MV. Arctic and an alternative system using as slow speed diesel with a fixed pitch open propeller. It was found that for a reasonable correspondence of thrust and speed as shown in Attachment 5.10, the slow speed engine would have to deliver about 17,500 DHP to the open propeller compared with about 14,500 DHP of the MV. Arctic system. When account is taken of all the installation and operational differences between the two systems, the cost advantage of the MV. Arctic amounts to about $3 million when discounted to net present value over a 15 year life-cycle. This represents a conservative comparison since it is possible that an open propeller would also be more susceptible to ice ingestion effects creating potentially greater loads and higher maintenance levels on the whole propulsion system.

5.9 Summary of findings

Certain important conclusions have been reached from the 1979-1981 test results concerning the effect of ice ingestion on the propulsion system of the MV Arctic. The main findings are as follows:

a) Transient torques and thrusts due to ice impacts on the propeller reach twice the mean level at maximum continuous rating of the engine. These effects exceed by about 50% the ice torque provisions of CASPPR and this exceedence might be significantly greater in the absence of the protection of a propeller nozzle.

b) Ice interactions with the propeller are of the single impact type and no evidence of ice milling has been identified. The more signficant ice impacts occur during broken channel operations and during pitch reversals when ramming. Impacts rarely occur during continuous mode transiting of level ice which is believed to be due to a combination of length of ship, underwater form, propeller submergence and nozzle protection which result in good ice clearing and deflection qualities.

c) Based upon the 2 MCR level of transient loading, theoretical considerations indicated that the propeller, shafting and gearing of the MV Arctic have adequate strength. However, bending effects on the shaft and thrust action on the gear case may give rise to longer term problems and require more detailed investigation.

d) Techno-economic considerations show worthwhile life-cycle advantages in favour of the medium speed diesel/c.p. propeller/nozzle installation of the MV. Arctic compared to a slow speed diesel/f.p. open propeller alternative. Safety considerations also appear to favour the as-fitted system.

These and other findings of the propulsive performance of the MV. Arctic indicate the need to re-consider some of the regulatory requirements for the machinery of arctic class vessels. In particular, the following provisions of CASPPR should be revised:

- The minimum power requirements should be based on continuous motion at a specified speed in level ice of a specific strength and thickness.

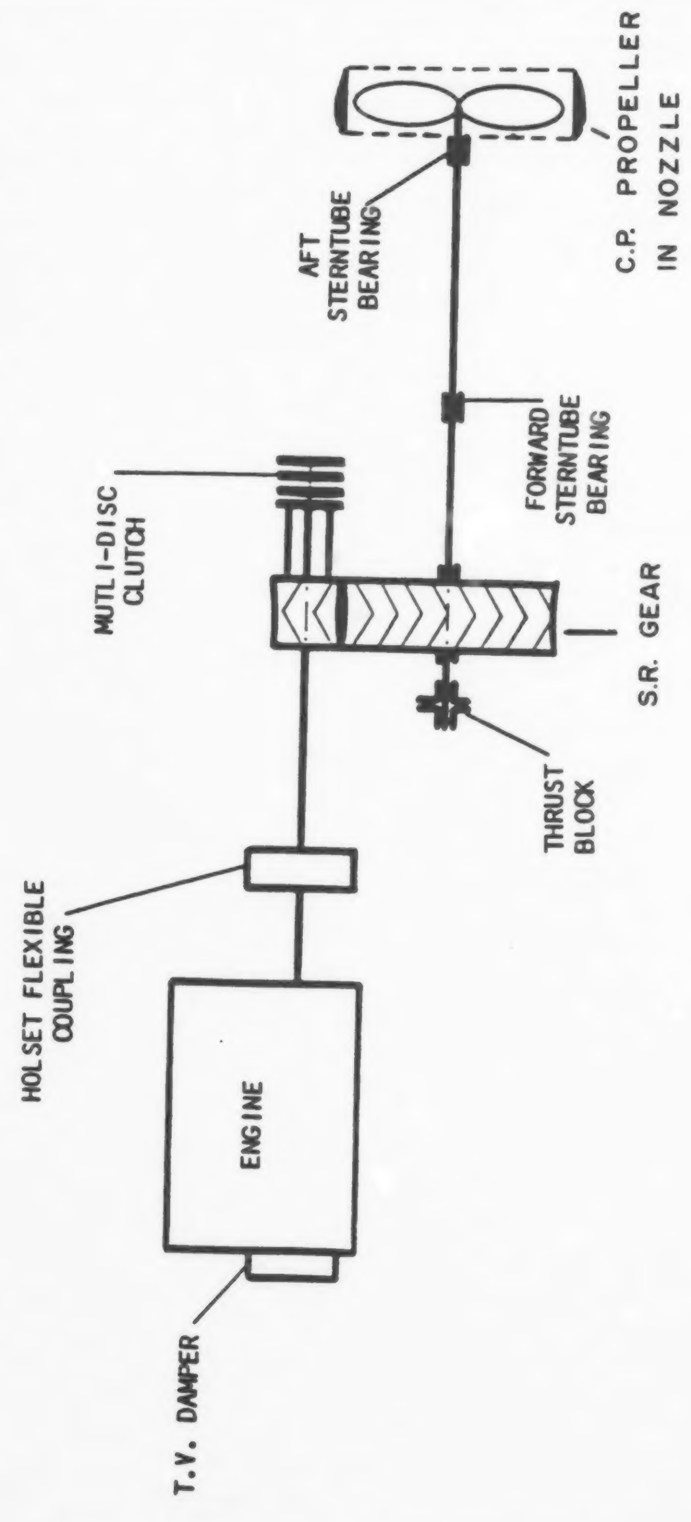
- The ice torque factor for the design of propeller, shafting and gearing should be revised to take into account the ice clearance and protection qualities of the particular ship form and propelling configuration involved.

- The effects of thrust as well as torque should be included in the provisions for machinery strength.

- The magnitude of disturbance allowed for ice effects in terms of torsional and axial overloads and vibrations should be specified.

In addition to the above, the provisions of CASPPR should incorporate a relationship between propulsive power requirements and structural strength of the hull to ensure compatibility of the total design.

SCHEMATIC ARRANGEMENT OF MV ARCTIC PROPULSION SYSTEM

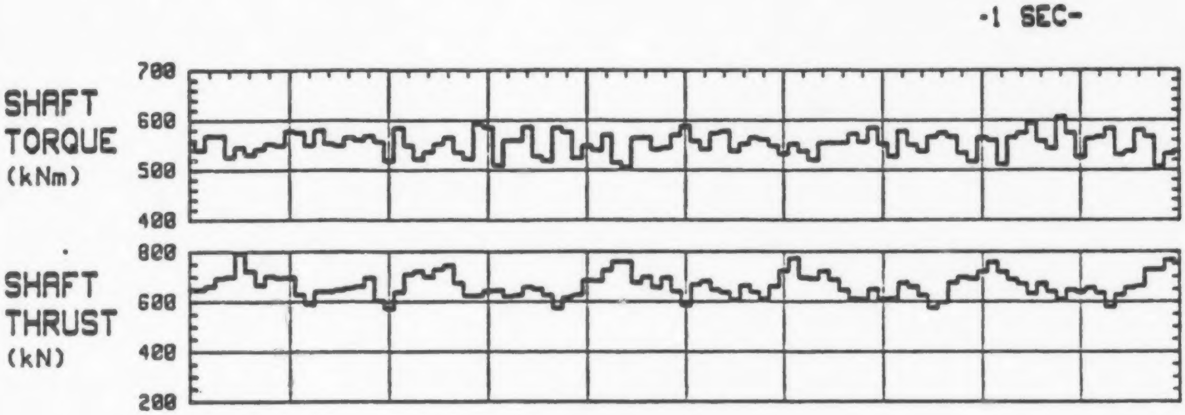


ATTACHMENT 5.2

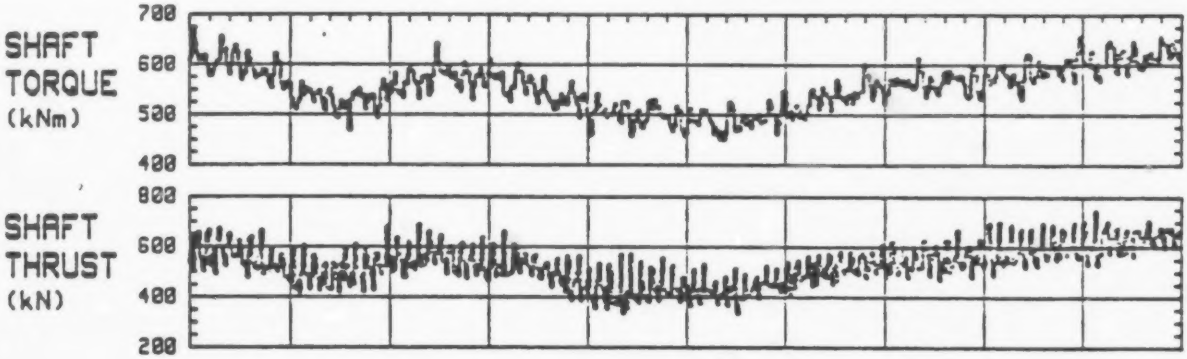
M.V. ARCTIC - PRINCIPAL PARTICULARS

Installed Power	14,770 BHP (Metric) 11,018 KW (S.I.)
a) Main Engine - M.A.N. 52/55A 14 Cylinder 450 r.p.m.	
b) Gearbox - Renk Single reduction, vertical offset, with 3.147 reduction ratio	
Propeller Diameter	5.27 m
a) Lips - Controllable pitch - four blades - single propeller - 143 r.p.m. located in Wageningen 19A nozzle with 25 mm tip clearance	
Bollard Pull at Full Power	160 tonnes
Classification - Lloyd's [✠100A1, Ice Class 1A Super, LMC] - Arctic Class 2 (CASPPR)	
Ballast Capacity	28,329 tonnes
Fuel Capacity	1,852 tonnes

ATTACHMENT 5.3



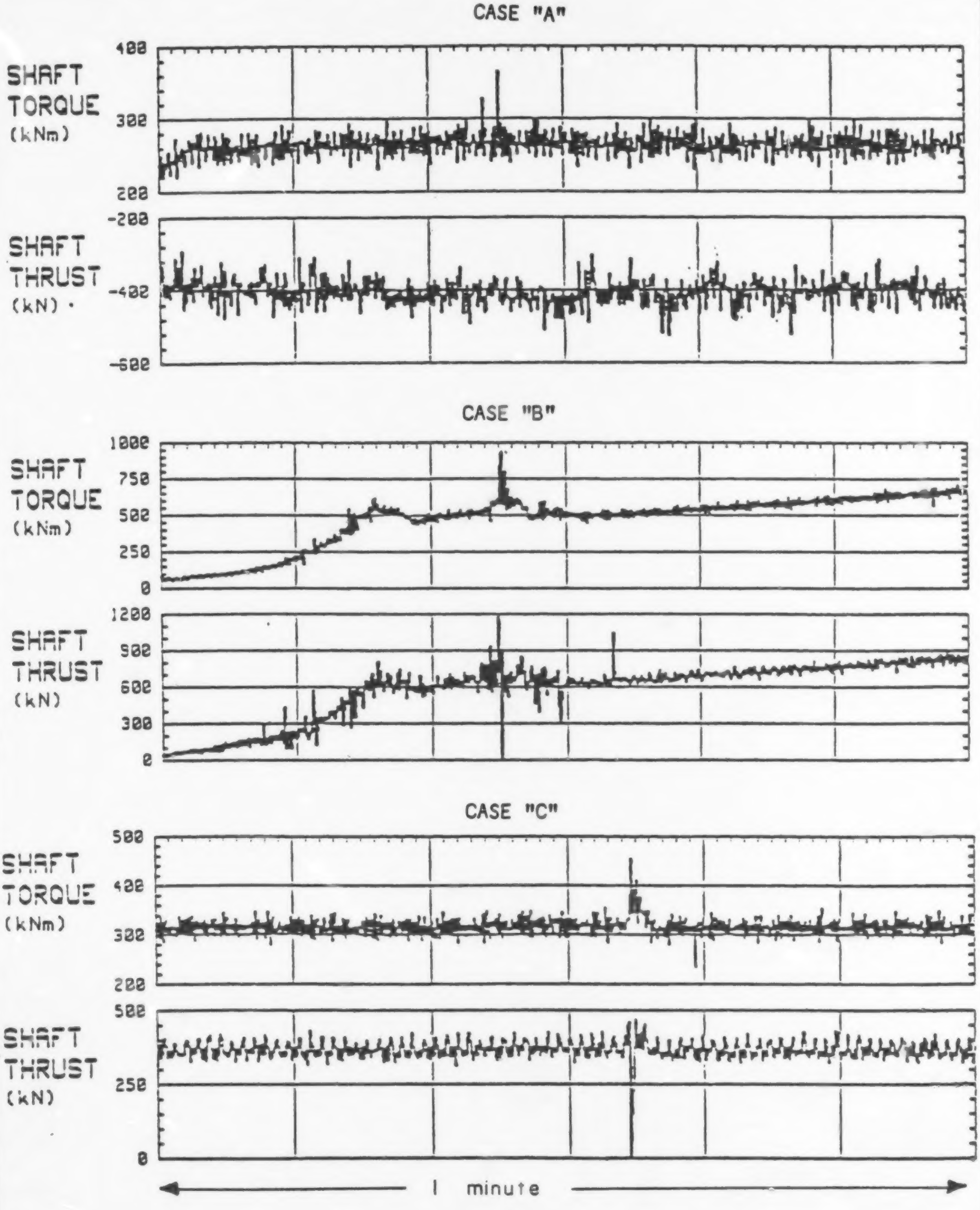
(A) SMOOTH SEASTATE



(B) ROUGH SEASTATE

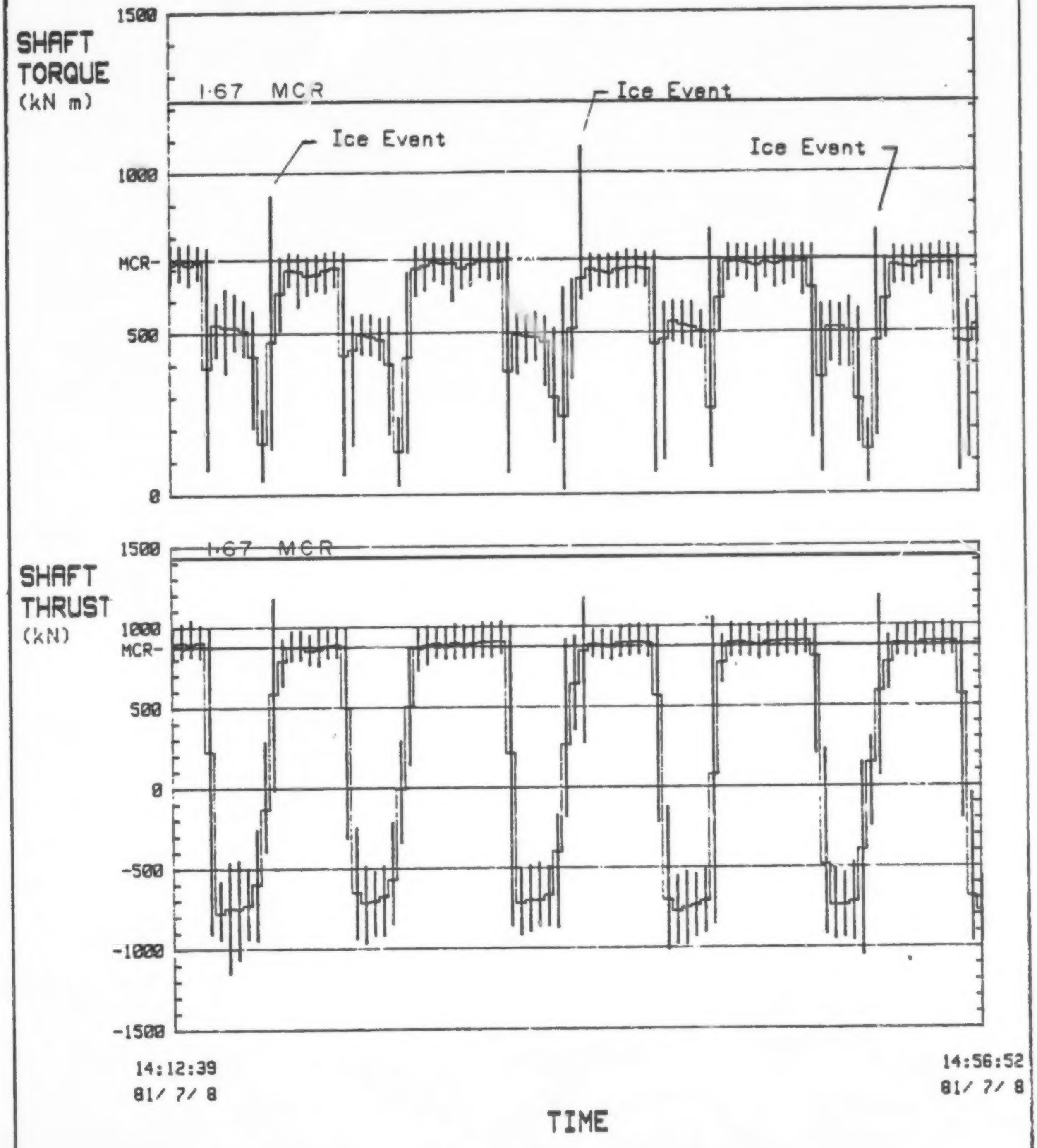
OPEN WATER RESPONSE

ATTACHMENT 5.4



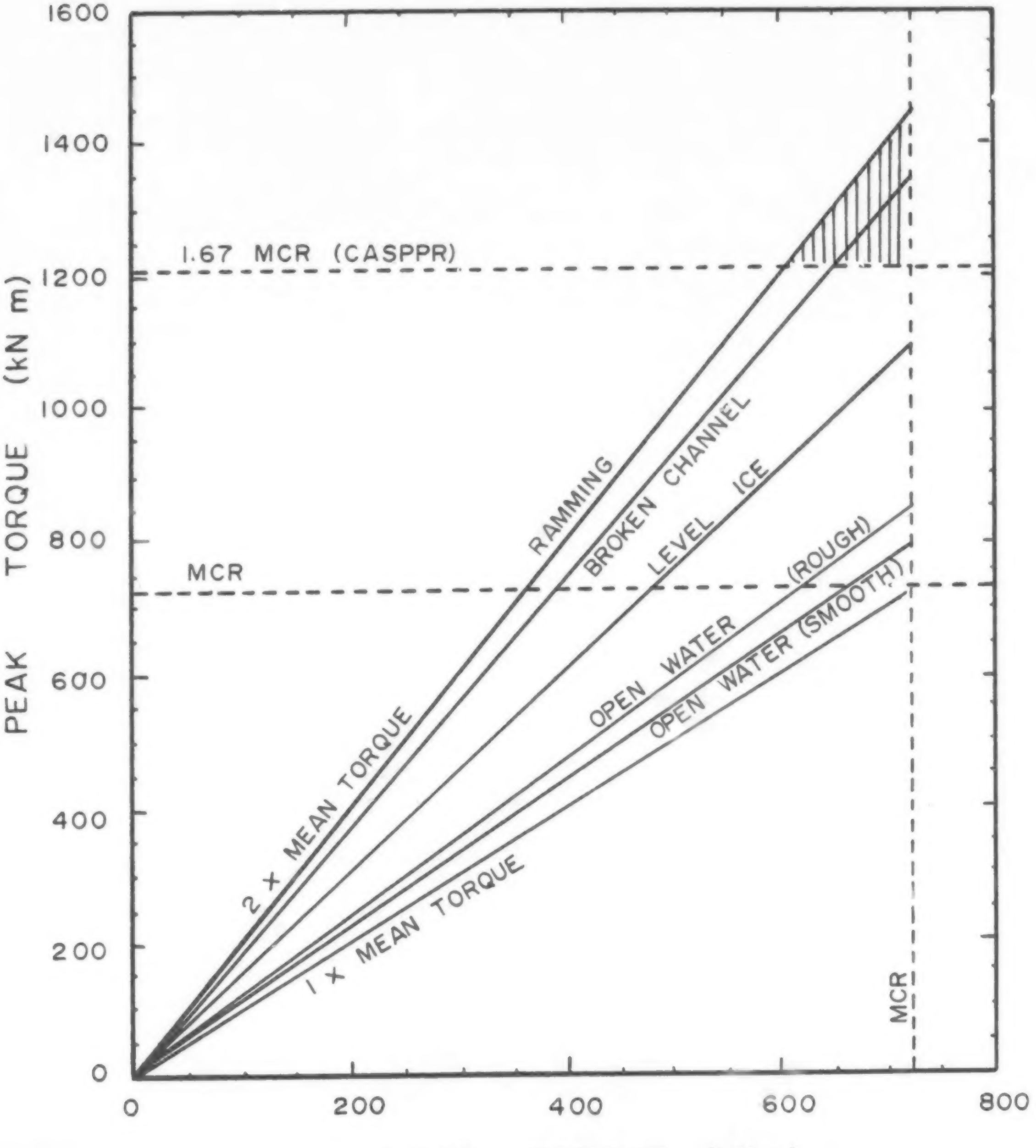
TYPICAL PROPELLER/ICE INTERACTION EVENTS

ATTACHMENT 5.5

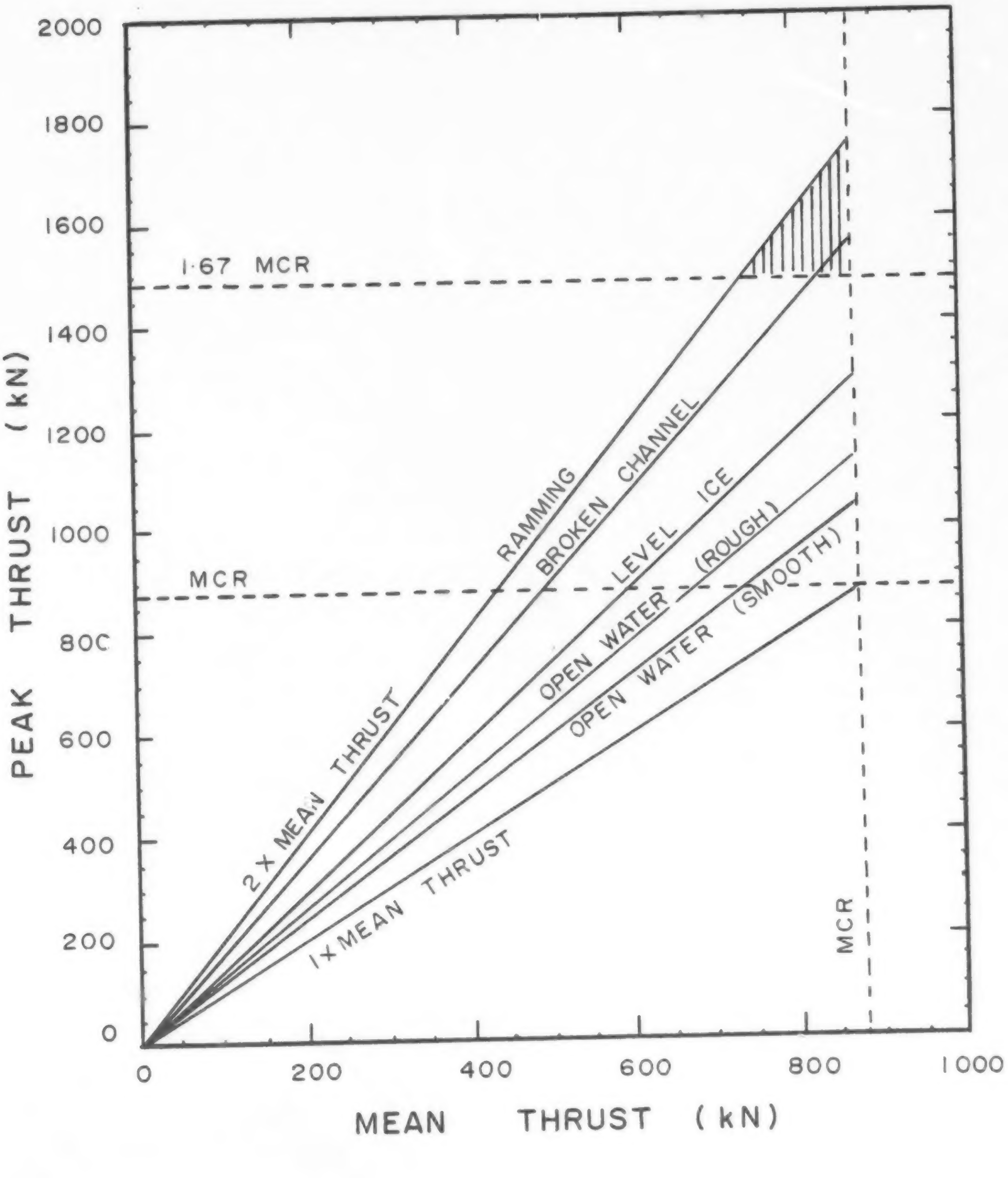


PROPULSIVE PERFORMANCE RECORD
(LEVEL ICE RAMMING)

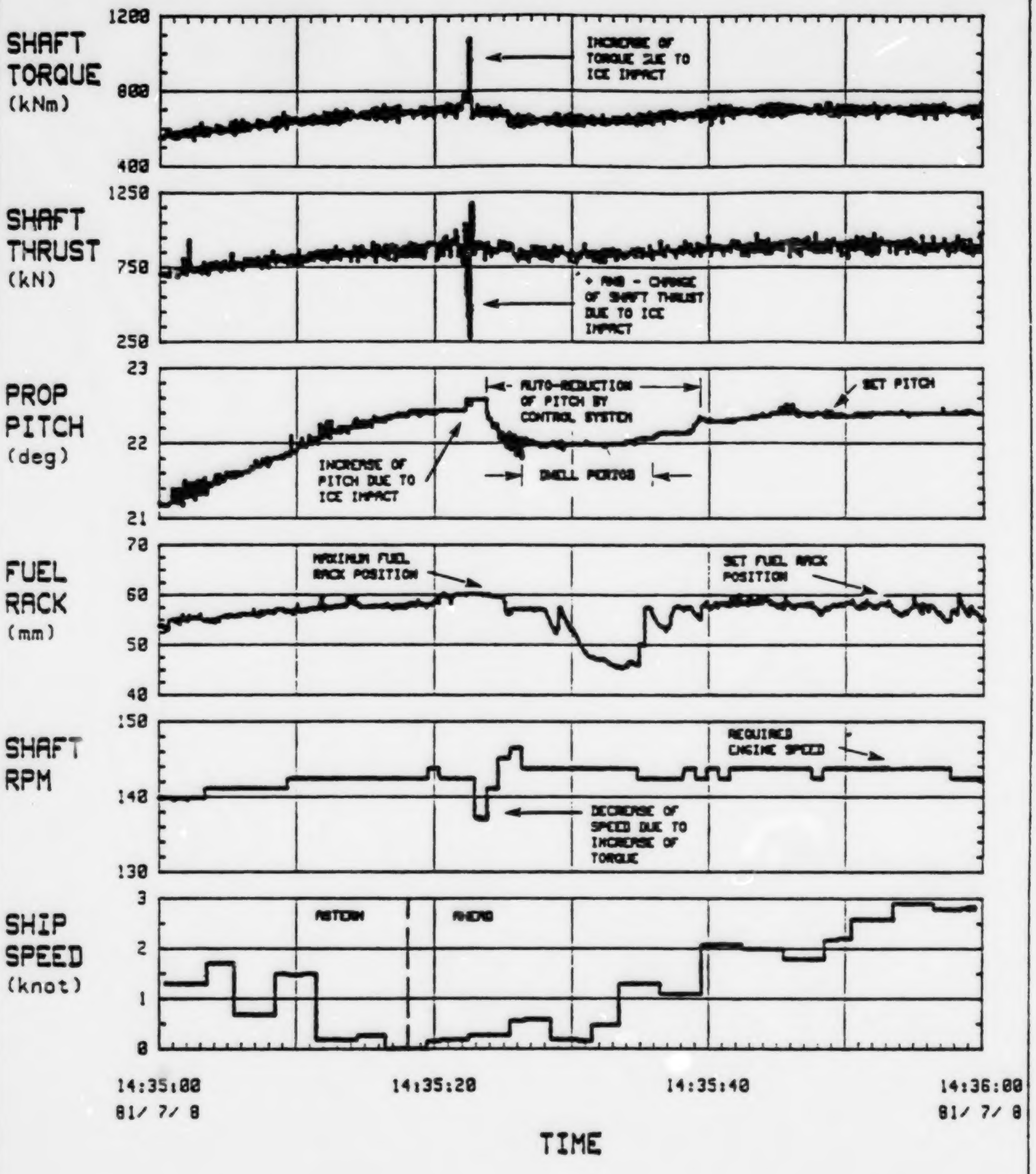
ENVELOPES OF TRANSIENT ICE TORQUES



ENVELOPES OF TRANSIENT ICE THRUSTS

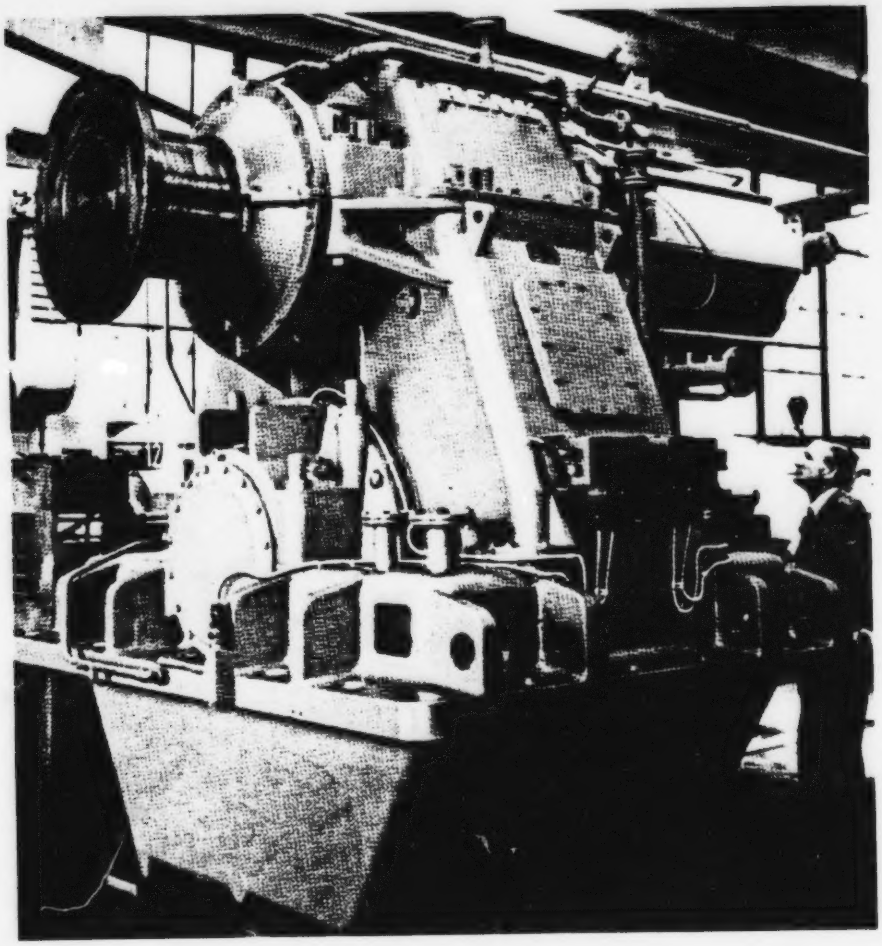


ATTACHMENT 5.8



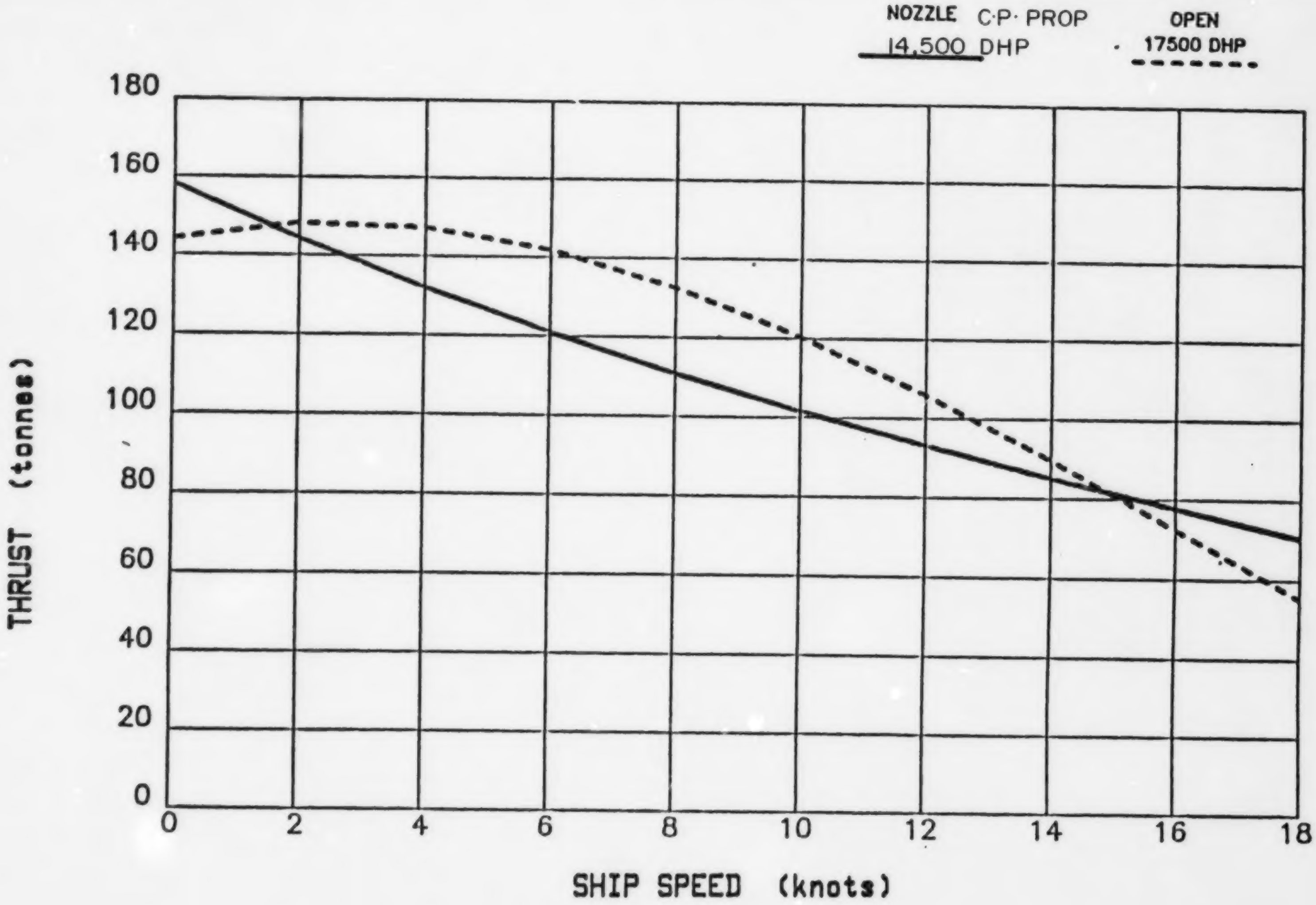
GOVERNOR RESPONSE DURING ICE INGESTION

M.V. ARCTIC REDUCTION GEAR



MV ARCTIC vertical offset single reduction gear integral with multi-disc clutch (upper right) and thrust block (lower left).

ATTACHMENT 5.10



PROPELLER THRUST VERSUS SHIP SPEED

SECTION 6

STRUCTURAL PERFORMANCE

6.1 Introduction

The MV. Arctic is the first Ice Class 2 bulk-carrier to be designed and built in accordance with the CASPPR provisions. Structural criteria are set down in those regulations which include ice pressures on various parts of the vessel's hull and form the basis for the determination of shell thickness, framing and stringer strengths. Classification Society rules for structural strength (in particular, the rules of Lloyd's Register) adopt the CASPPR criteria for vessels such as the MV. Arctic whose ice class requirements exceed the Society's rules for ice-strengthened ships. Accordingly, the evaluation of the structural response to ice interaction under the various ice-transiting conditions experienced in the arctic zones and seasons, permitted by CASPPR for this class, was a major objective of the MV. Arctic Scientific Program. The results obtained are summarized in this section of the report.

6.2 Structural instrumentation

The hull of the MV. Arctic was instrumented with strain gauges in four arrays as shown in Attachment 6.1. All arrays were fitted on the starboard side, one of which was repeated on the port side as indicated. Arrays I, II and IV totalled 169 strain gauges and constituted the original installation in 1979 whilst Array III, comprising a further 26 strain gauges, was added in 1981 to extend the coverage of the bow region. The basic structural components of the ship's hull are shown in Attachment 6.2 and consist of a double skin supported by webs, frames and stringers. The orientation of the strain gauges over the three bow region arrays is provided in an attachment to Section 7 of this report.

A finite element model was prepared, principally for region II, and used for the optimal placement of the gauges as well as for the subsequent determination of structural loads resulting from hull-ice interaction. After installation in 1979, the strain gauge arrays were calibrated by applying known loads to the hull for the purpose of determining the relationship between the loads and the strains recorded by the gauges.

6.3 Database validity

As an important preliminary to the reduction and analysis of the data recorded by the instrumentation system various tests were performed to validate the database. These included verification of the position and functioning of the extensive array of structural strain gauges, the elimination of gauge zero drifts and confirmation of the raw signal conversion factors. In addition, further tests were performed as analysis proceeded to confirm the validity of the results being generated. An example of one such test is shown in Attachment 6.3 where the calculated ice loads on the ship were compared with the results from other icebreaking ships on a baseline of an ice-strength/ ship-velocity parameter. It is evident from the diagram that the majority of the spots representing the MV. Arctic reduced data lie well within the envelopes surrounding the data groups of the other four ships and exhibit similar trends and characteristics. Test procedures such as these lead to the conclusion that the database is valid and dependable for reliable analysis.

6.4 Ice pressures

The structural requirements for arctic vessels are based upon the hull strength needed to withstand specified ice pressures. The pressure specification varies in the different areas of the ship's hull, being highest in the bow where the greatest intensity of hull/ice interaction occurs. The specified ice pressures also vary in relation to a scale used to denote the ice class of the ship. These variations are set down in the CASPPR provisions as shown in Attachment 6.4. It will be seen that for the MV. Arctic, an Ice Class 2 vessel, the bow area strength requirement is to be based upon:

Bow area ice pressure = 4.14 MPa.

As described in Section 6.2, the bow area of the MV. Arctic was extensively instrumented with strain gauges as the prime area of structural investigation. The data recorded from these sensors, over a three-year arctic operating period, has been used to determine the level of ice loads and resultant pressures experienced at the bow under the following five ice-transiting modes:

Mode 1	Ramming in thick ice and ridges
Mode 2	Continuous in level ice with multi-year floes
Mode 3	Continuous in homogeneous level ice
Mode 4	Continuous in broken channel
Mode 5	Turning in level ice.

The analyses were extended to determine the probability of occurrence of extreme pressures in the five modes and the results are compared with the CASPPR bow design pressure in Attachment 6.5. It will be seen that in continuous level ice (Mode 3), there is negligable chance of design pressure exceedence, whilst in the other four modes low probabilities exist. The greatest of these is associated with the presence of multi-year ice floes (Mode 2) and it has been in such ice conditions that some hull damage has occurred. The risk of damage is also significant in broken channels where higher ship speeds are possible and result in greater velocity of impact with ice pieces. Whilst the probabilities of design pressure exceedence are low, recognition must be given to the possibility, however, that the ship may occasionally experience pressures several times larger than specified.

A pressure severity ranking of the five modes based upon 0.98 probability level is provided below:

Multi-year floes	: 6.1 MPa (2.4 x level ice)
Broken channel	: 5.0 MPa (2.0 x level ice)
Ramming	: 4.1 MPa (1.6 x level ice)
Turning in level ice	: 3.4 MPa (1.4 x level ice)
Level ice	: 2.5 MPa (1.0 x level ice)

The number in brackets is a derived severity index which expresses the ice pressure (at 0.98 probability or 0.02 risk) in terms of a reference ice pressure for continuous level ice operation. Investigations were also undertaken to detect the variations of pressure due to ice thickness and ship speed. The scope of the database was sufficient only to detect a slight lineal pressure relationship in these two quantities. Even though these trends are only faintly discernible from this database, it is reasonable to expect that such relationships do exist and, if quantifiable, would provide a useful link between hull strength and propulsive power.

In the foregoing, the ice pressures are based upon a two-step process; the first of which was to determine ice loads from the measured strain data using a special strain-to-load conversion algorithm. The ice loads are carried by the main matrix of web frames and stringers and thus the overall ice pressures can be logically represented by the uniform distribution of the loads over the 1.5 m^2 basic panels of shell plating which span this matrix. The overall ice pressures, therefore, were obtained by dividing the ice loads by the above panel area.

This presumes that all parts of the plate panel contribute equally to the support of ice pressure which is unlikely in view of the fragmented and uneven contact of the ice with the hull. Under such conditions, however, it is believed that ice bridging takes effect whereby highly localised loads are shed by the plates into the stiffer frames and ultimately into the main webs and stringers. Accordingly, the investigations were further extended to examine this phenomenon through a closer study of the effect of area of ice contact on the resultant localised pressure.

The result is shown in Attachment 6.6 for Modes 2 and 3, each of which show similar trends. In each case, the vertical bar represents the variation of overall ice pressure on the basic 1.5 m^2 shell panel. The sloping line represents the variation in local ice pressure on smaller contact areas within the basic panel. Those results show that, at the lower end of the sloping line where the area of local ice contact is relatively large, the local ice pressure tends to fall below the overall ice pressure indicating that load shedding (ice bridging) is taking place. On the other hand, at the upper end of the sloping line where the area of ice contact is very small, the local ice pressure becomes several times larger than the overall pressure indicating that load shedding is absent. The significance of this is immediately apparent when related to the indicated CASPPR design level.

It is evident that plate rupture is much more at risk from the highly localised ice pressures than from overall pressures and leads to the conclusion that plating strength should not be based upon the phenomenon of ice bridging. The fact that the same result occurs in both the easiest and most difficult ice-transiting modes (Modes 2 and 3) attaches a special importance to the above conclusion.

6.5 Hull stresses and strains

The previous sub-section addressed the subject of hull pressure due to interaction with various types of ice. It is now of considerable interest to examine the levels of stress experienced by the hull and, in particular, the plate and frame stresses occuring under the various ice-transiting modes. Again, the two reference modes 2 and 3 are selected and the stress distribution for each are shown in Attachment 6.7. The upper diagram in each case shows the variation of stress along four waterline levels, whilst the lower diagram shows contours of stress superimposed on the side view of the ship's bow. The following observations are made on these diagrams.

- For continuous operation in multi-year floes, the location of the peak stresses is concentrated in the shoulder area, at and below the waterline. The area between stringers 4 - 4A exhibits lower stresses aft. The location reflects an expected operational effort to avoid hitting multi-floes "stem-on". Stress levels in frames and plates at the shoulder were found to be higher than those observed in the ramming mode. Highest plate stress occurs aft and low. While this additional information does little to resolve the cause of the area of lower frame stress at stringer 4A and frames 170-180, the evidence supports the theory that as the ice breaks up, it causes more local loads which tend to stress the plates to a greater degree than that produced by higher loads on the frames.

- In continuous level icebreaking, stress levels are generally lower than in the other categories. Plate and frame gauges exhibit similar levels, and the stress level is virtually identical thoughout the waterline length. The higher stresses are concentrated at the lowest waterline, as measured by the frames, but could not be qualified by plate data due to insufficient data points. The pattern reflects the generally lower stress levels associated with bending failure of cusps along the hull, but it is interesting to note that high stress levels are experienced due to wedging the turned pieces at and below the edge of the unbroken sheet, when crushing takes place.

The percentage occurrence of frame stresses are shown in Attachment 6.8 as histograms which reveal noticeable pattern differences between the two modes and between the two waterline levels.

The foregoing and similar analyses conducted on the other ice transiting modes demonstrate the fact that the location and the distribution of peak stresses in plates and frames are not identical and arise from different ship/ ice interaction responses. In general, it is noticed that peak plate responses are the result of local loading caused by smaller ice pieces. The frames react to larger area loads and the phenomenon of "bridging" in these larger areas results in lower responses in the plates. This is the same bridging effect as was reported in the previous sub-section on ice pressure.

The investigation of structural stresses due to ice loads was extended into extreme value predictions. The results are shown in Attachment 6.9 for plates and frames. The risk of exceeding the yield stress criterion of CASPPR is significant as was found with ice pressure. Again, the multi-year ice transiting mode carries the highest risk for plates and frames, whilst in all modes plates are at higher yield risk than frames.

It is concluded that the plating does not appear to have adequate margin against failure and that the specification of shell thickness in CASPPR, whether based on simple or plastic yield, results in at least a high probability of permanent set in the plate. It is further concluded that the frames are at much lower risk than the plating and hence, the strength level specified in CASPPR, although borderline, may be acceptable. It must be noted, however, that regulations for plates, frames, webs and stringer strengths adopt ice loading as the basic criterion. Accordingly, it would seem logical that tests of adequacy of structural strength criteria should focus initially on design ice pressure specifications.

It must be added that structural strength is not only a function of the loads to be withstood but also the rate of load application. A close investigation of the recorded strain patterns has revealed that the strain rates being experienced are several orders of magnitude below the rate critical to crack propagation. Accordingly, whilst the foregoing has reported that risk of structural yield is present, there is no associated risk of the more dangerous situation of crack propagation.

6.6 Structural damage

During the three-year program of data acquisition, five events of structural damage were recorded and analysed. The location of these events are shown in Attachment 6.10 and have two main centres of occurrence, namely the forward bow and the shoulder regions. The hull/ice interaction process during these events is informative of the mechanics of ice failure.

In Case 3, a multi-year floe impact, an attempt was made to reconstruct the impact conditions from strain measurements, as shown in Attachment 6.11. It is shown that the contact with ice spread over the extent of the bow with two major contact locations. At the forward location, the impact was centered about the light load waterline, while at the aftward location the impact was a couple of stringer spacings below that level. The forward impact indicates the load position moving forward versus the initial impact caused by ice failure. It should be noted that the ship was in cargo condition and was progressing in continuous mode in level ice at six knots when she hit a multi-year floe. Based on strain data, minor dent (indentation) of the hull may have occurred between frames 192 and 195 as well as frames 179 and 183. Using the results from the load calculation, it is projected that maximum ice load in the latter location is 14.45 MN (1473 tonnes). At the foremost location, in the vicinity of frame 192 and light waterline, the maximum strain was higher and the load was estimated to be of the order of 19 MN. The figure illustrates that the nature of ice failure is of continuous crushing failure limited by irregular fracture at the forward part of the bow. Some evidence exists of progressive crushing and possibly bending/shear failure closer to the shoulder.

It should be noted that all five cases involved the presence of multi-year ice. In two incidents, the heavy loads and local yielding occurred while the ship was manoeuvering in ice to position herself for ramming multi-year ice. The other three occurred during normal progress in level ice or pack ice fields when the ship hit multi-year ice floes at relatively moderate speeds of progress of the order of 5-7 knots.

6.7 Summary of findings

A number of important conclusions are reached from the analysis of the 1979-81 database concerning the structural performance of the MV. Arctic. The principal findings are as follows:

a) The level of structural response in the bow area of the MV. Arctic indicates a negligible risk of design strength exceedence in first year level ice operations. The risk increases in significance in other ice-transiting modes being greatest in the presence of multi-year floes.

b) The shell plating is more liable to experience damage due to ice loads than the associated framing. In particular, ice pressure on the shell is found to vary inversely with the area of ice contact so that localised ice pressures can be several times larger than specified for design.

c) The variations of pressure due to ice thickness and ship speed are found to be only faintly discernible from the available database. Such relationships, however, may be expected to exist and may be significant.

d) The pattern of plate and frame stresses over the bow region is distinctly unique to each ice transiting mode. In particular, the zone of highest structural stresses tends to move away from the shoulder and towards the stem as the ice thickness and strength increases.

e) The effect of load shedding due to ice bridging is not as beneficial in reducing plating pressures and stresses as is generally believed. Accordingly, it is concluded that plating strength should not be based upon the ice bridging phenomenon.

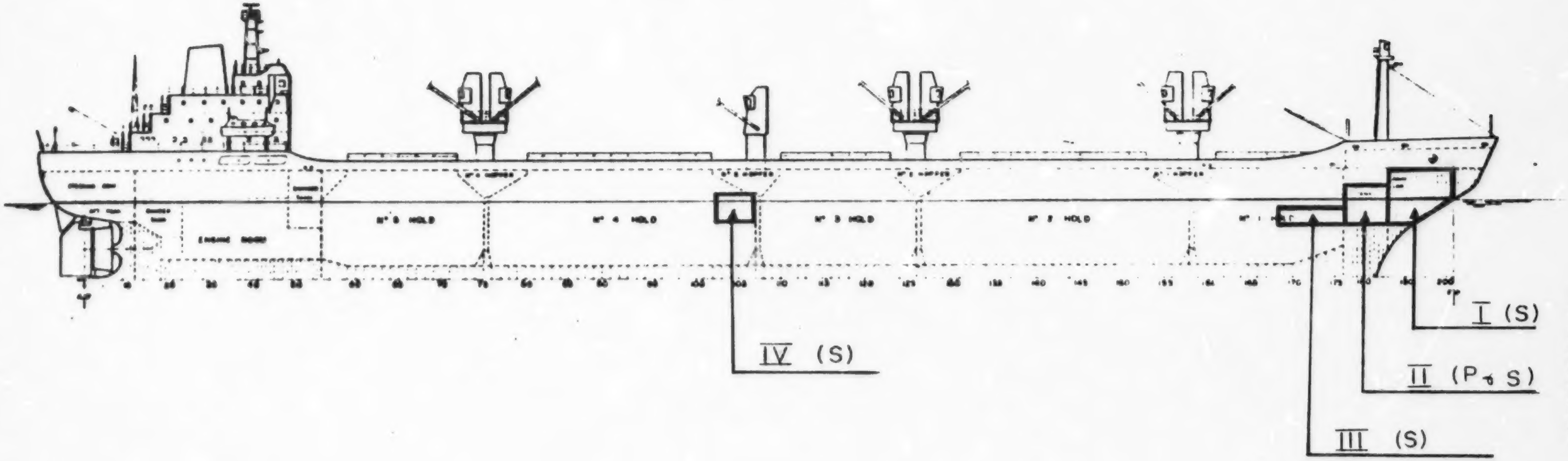
f) The strain rates experienced by the structure during the various ice-transiting modes are several times lower than needed for crack propagation. This means that although strains are sufficient to cause yielding of the structure, the damage will be localised and not extended by crack development.

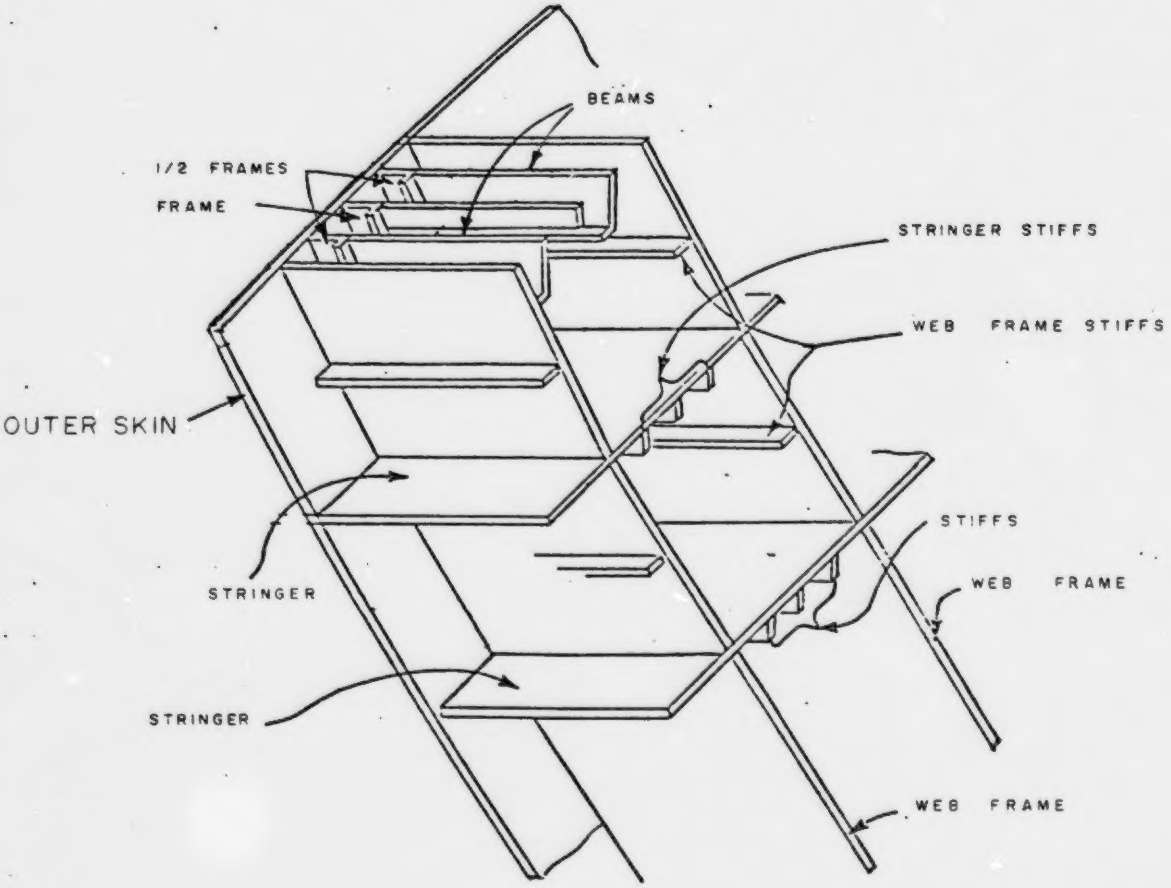
g) Despite the fact that the MV. Arctic modes of operation may cross the threshold of design strength, very few incidents of structural damage have been recorded and then only in the presence of multi-year ice.

This completes the main findings on structural performance except as they may impact on the criteria for hull strength design. In that regard, it is concluded that consideration should be given to the level of ice pressure which the structure is to withstand. In addition, consideration should be given to an appropriate relationship between hull strength, ice-transiting capabilities and propulsive power to ensure compatibility of the total design.

ATTACHMENT 6.1

M·V· ARCTIC - STRUCTURAL SENSOR ARRAYS

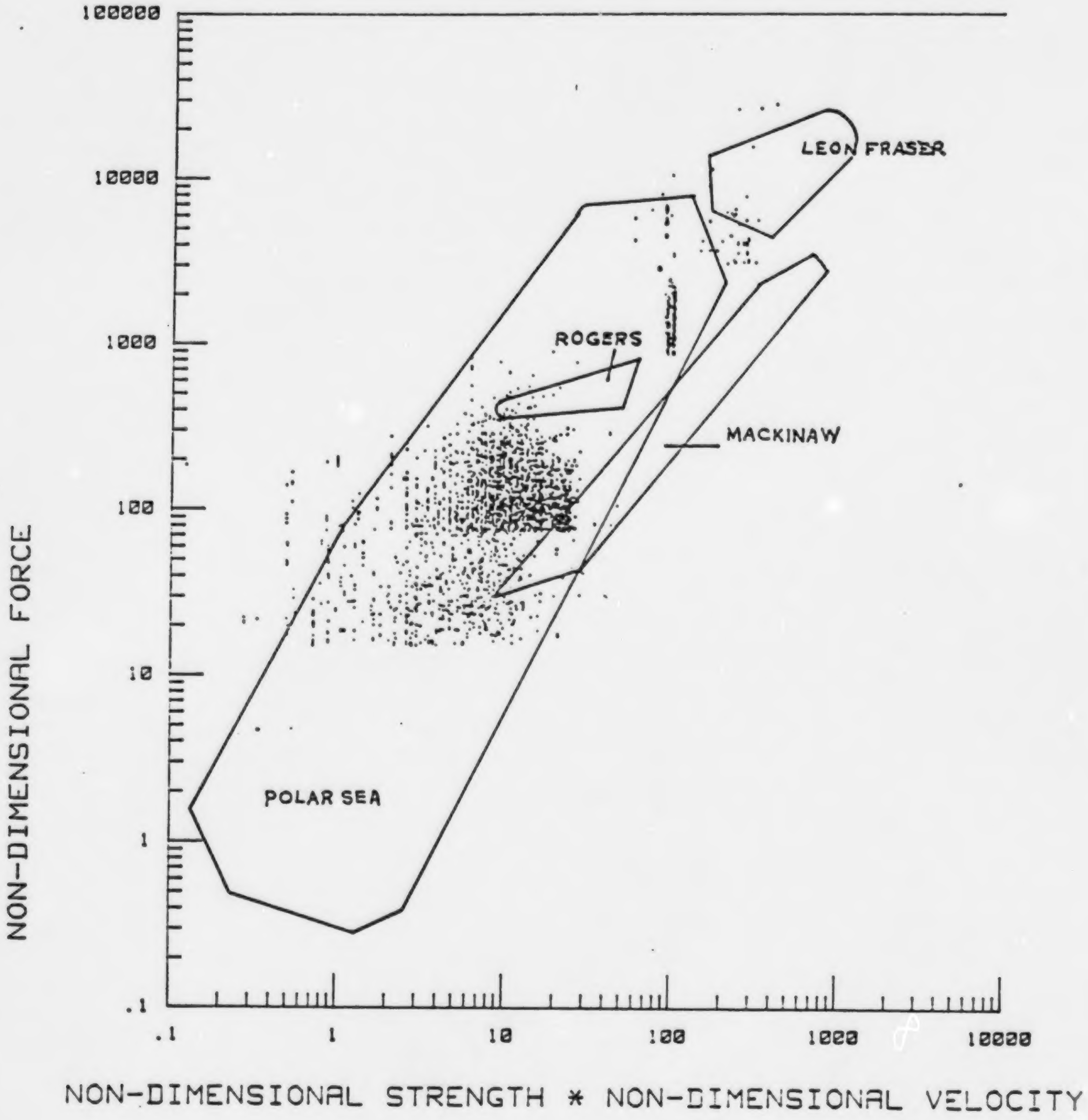




NOTE: THE INNER SKIN IS NOT SHOWN

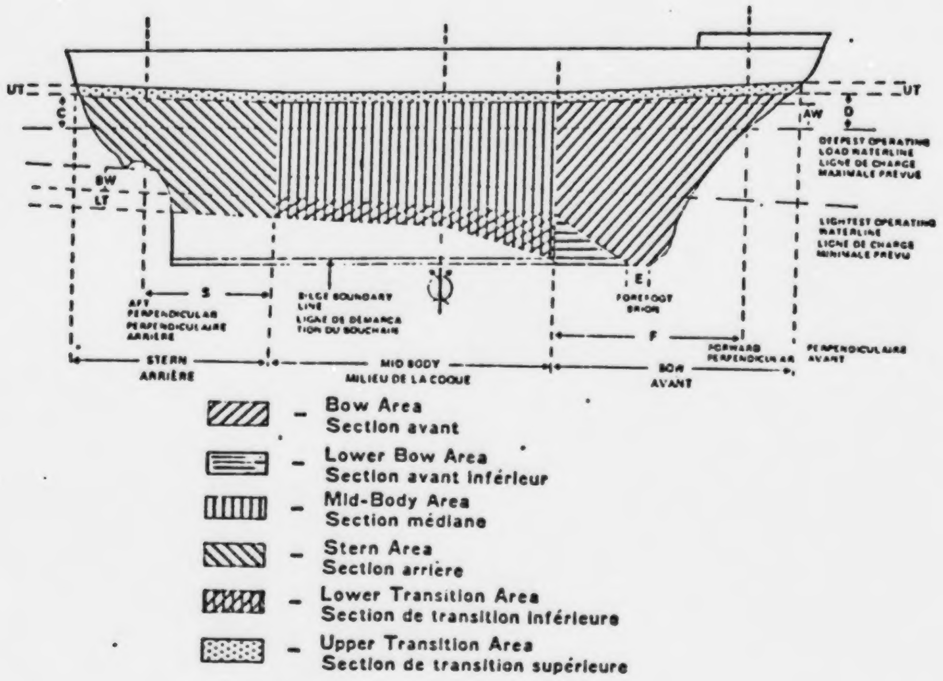
BASIC STRUCTURAL COMPONENTS OF SHIP HULL

RELATIONSHIP OF NON-DIMENSIONAL DATA



CASPPR RULES

HULL STRENGTH CRITERIA



Ice Pressures in megapascals

Column I	Column II	Column III	Column IV	Column V	Column VI	Column VII
Arctic Class	Bow Area	Lower Bow Area	Mid-body Area	Lower Transition Area	Upper Transition Area	Stern Area
1	1.72*	**	0.69*	**	**	0.69*
1A	2.76	1.45	1.79	1.24	0.90	2.24
2	4.14	2.21	2.76	1.79	1.38	3.45
3	5.51	2.90	3.65	2.55	1.79	4.55
4	6.89	3.65	4.55	3.17	2.28	5.65
6	8.27	4.41	5.17	3.59	2.55	6.48
7	9.65	5.10	5.86	4.14	2.90	7.24
8	10.34	5.52	6.55	4.55	3.24	8.27
10	10.34	5.52	6.55	4.55	3.24	8.27

*In an Arctic Class 1 ship, only that part of

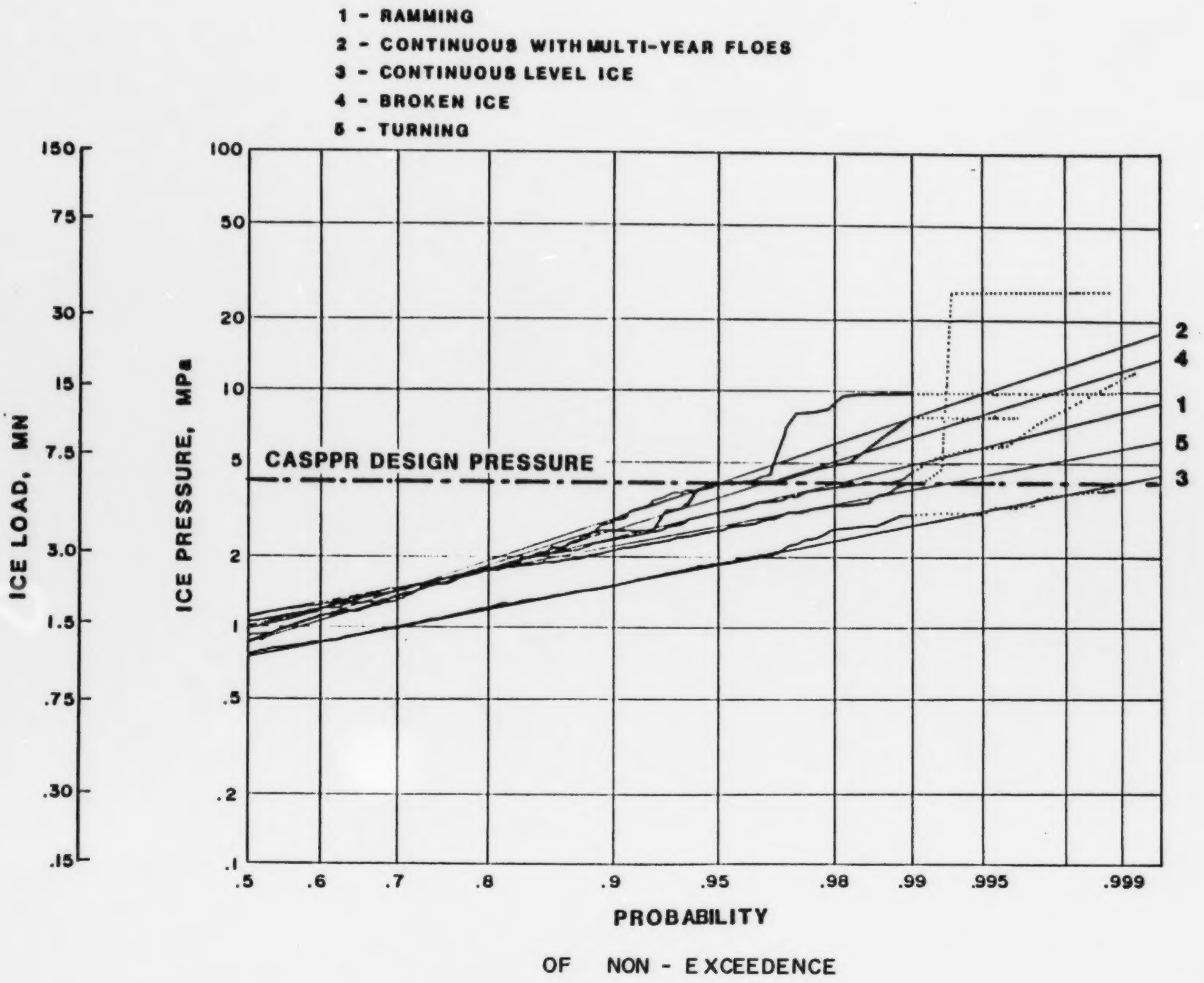
(*a*) the bow area and stern area lying between the horizontal projections of the upper and lower edges of the mid-body area need be considered; and

(*b*) the mid-body area forward of amidships need be considered.

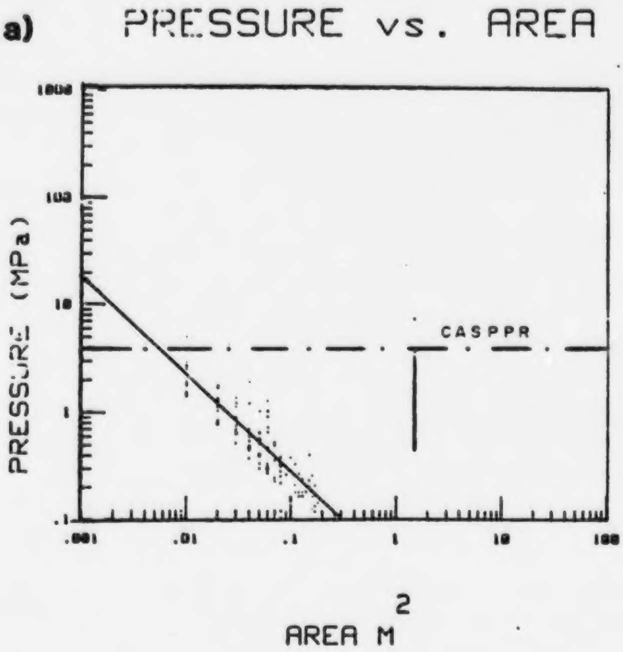
**In an Arctic Class 1 ship, ice pressure need not be considered as a factor in the design of the hull in the lower bow area, lower transition area and upper transition area, and the strength standards usually applied to ocean-going ships shall apply in these areas

ATTACHMENT 6.5

LOAD PANEL PRESSURE

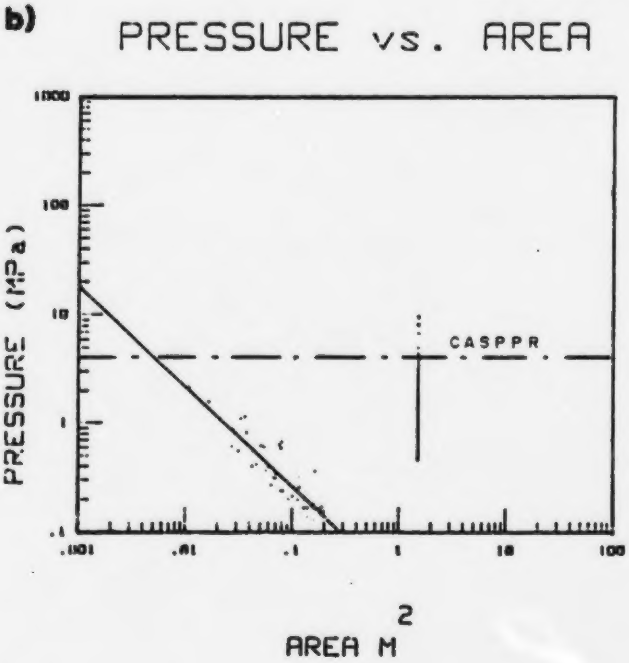


a)



CONTINUOUS LEVEL ICE
Data points = 1388

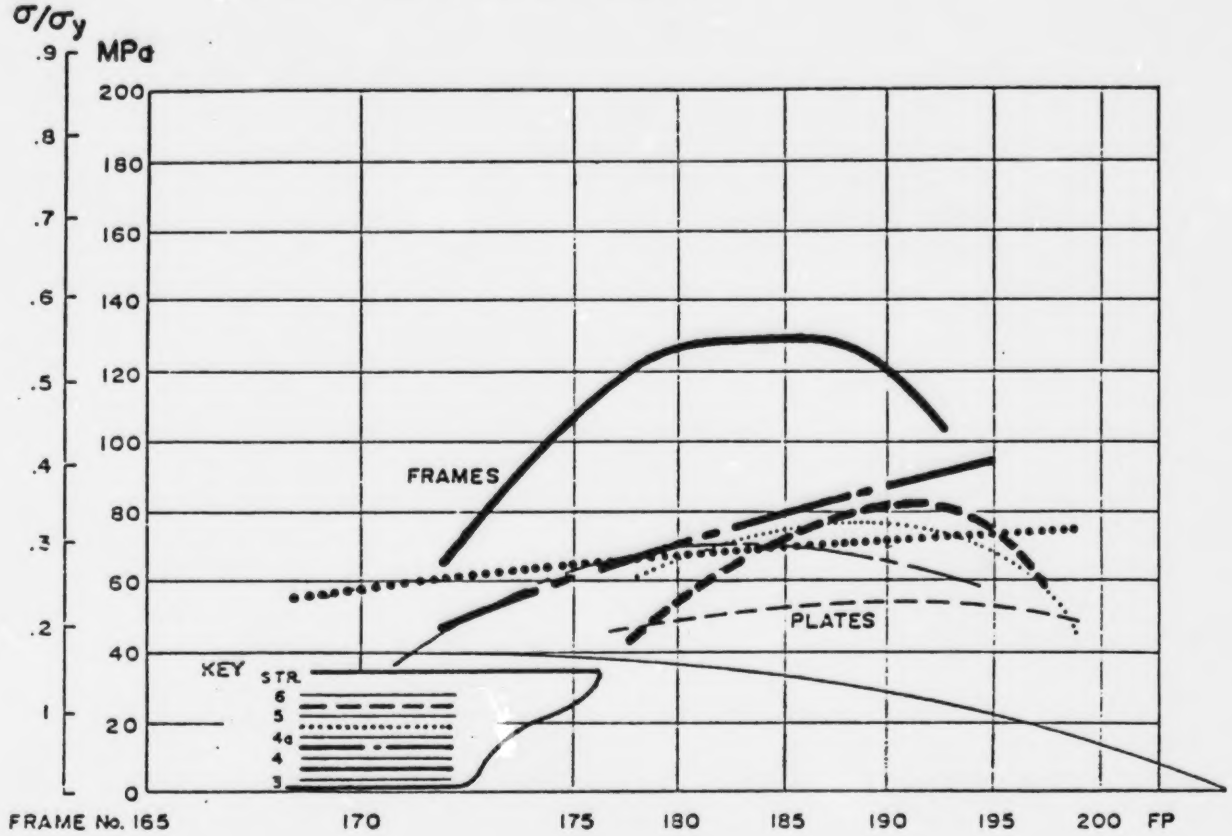
b)



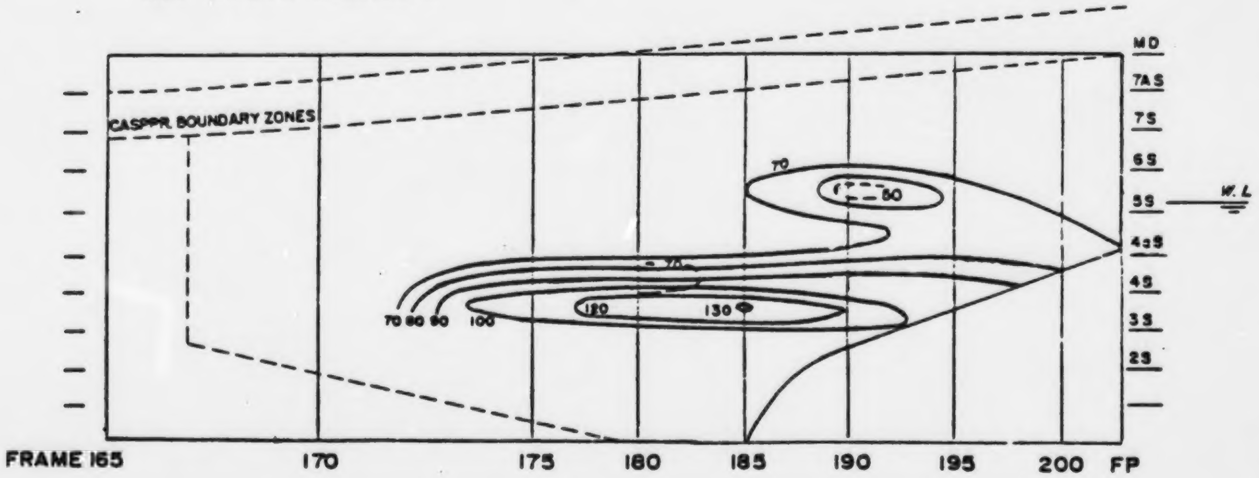
MY FLOES
Data points = 493

STRESS DISTRIBUTION - CONTINUOUS LEVEL ICE

Peak*stress profiles along waterline



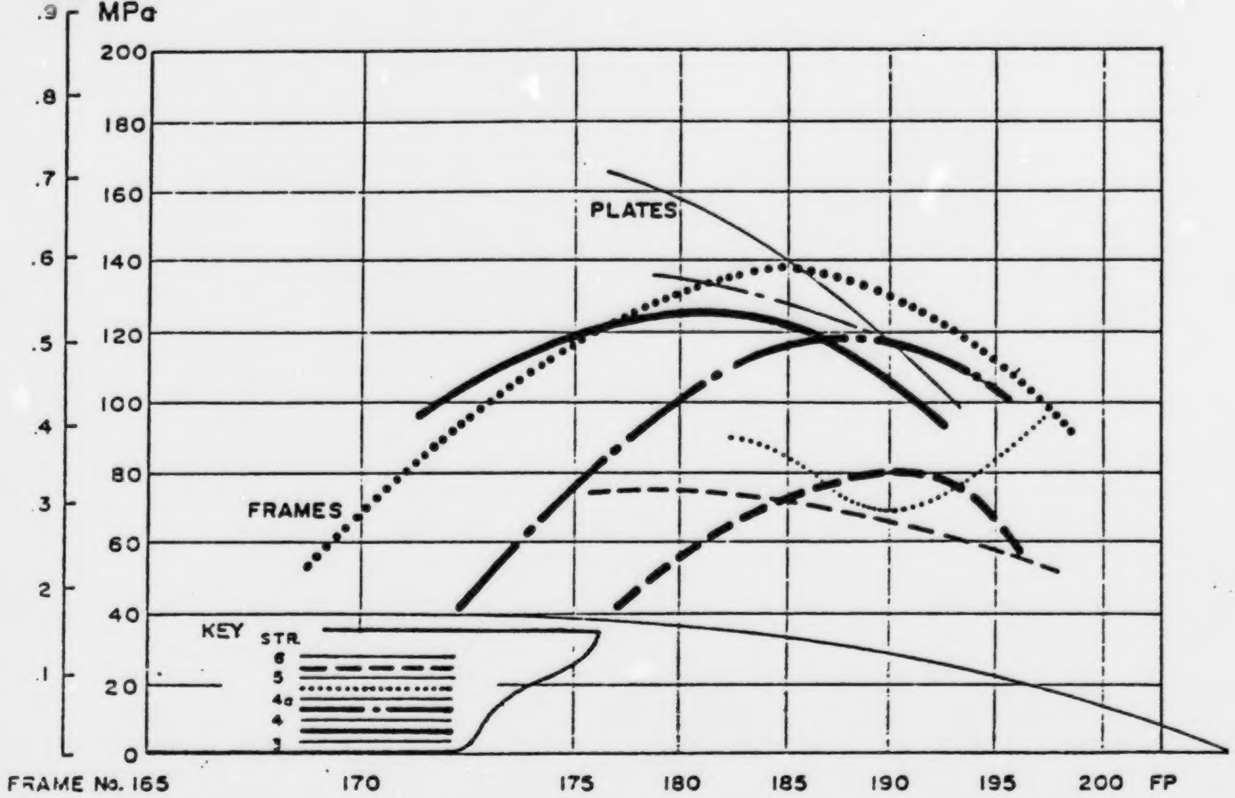
Iso-stress contours



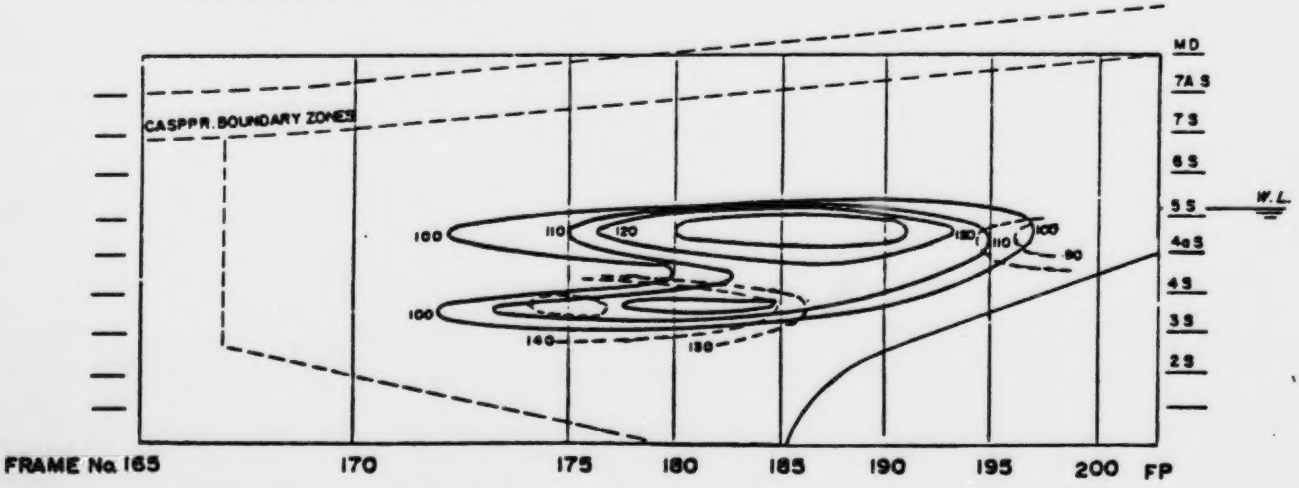
* REPRESENTS PEAK OF 90% OF DATA

STRESS DISTRIBUTION - MULTI YEAR ICE

Peak * stress profiles along waterline



Iso-stress contours

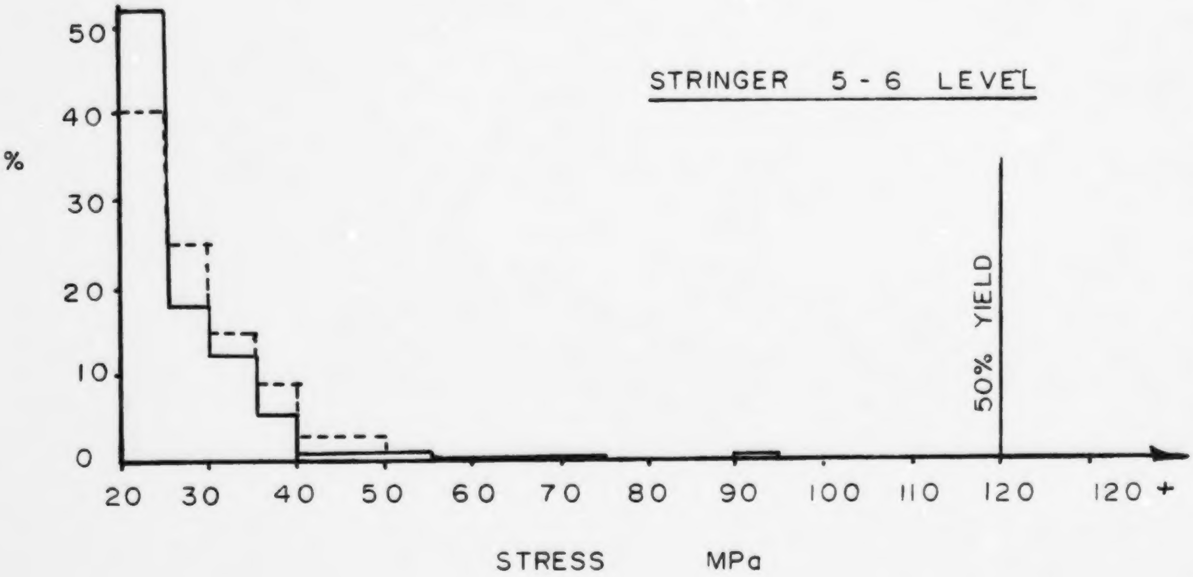


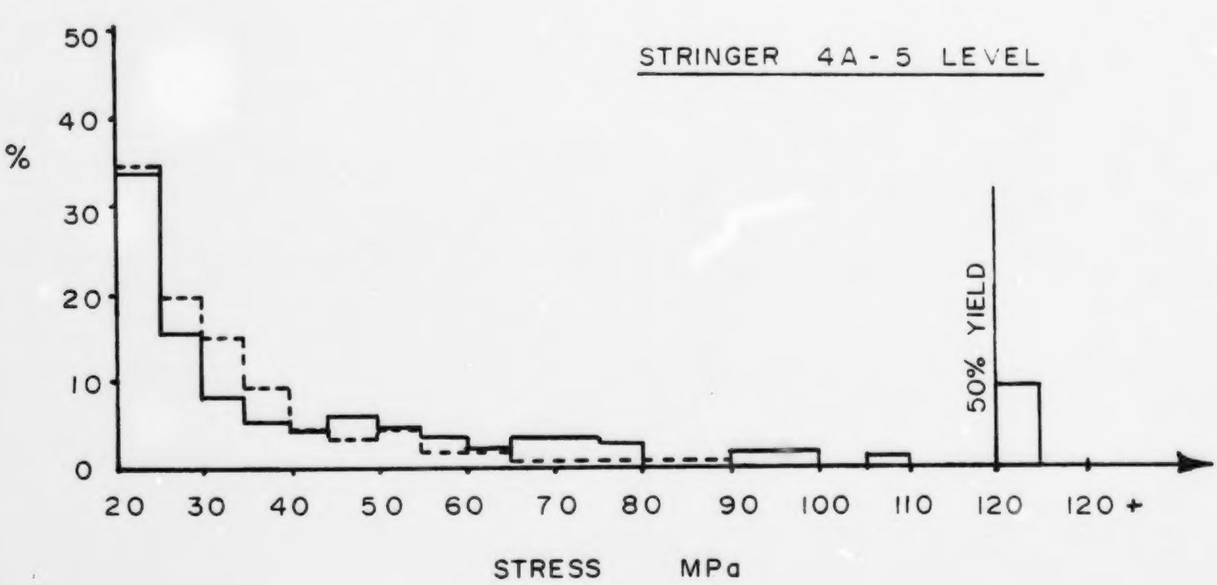
* REPRESENTS PEAK OF 90% OF DATA

ATTACHMENT 6.8

HISTOGRAMS OF FRAME STRESSES

——— MULTI-YEAR (Mode 2)
- - - - - - - CONT LEVEL (Mode 3)

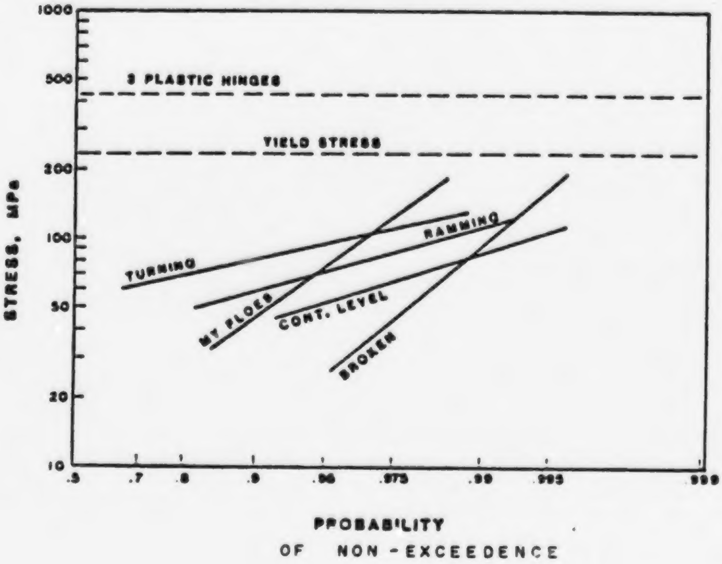




EXTREME PLATE STRESS DISTRIBUTION

(ENVELOPE OF ALL PLATE DISTRIBUTIONS)

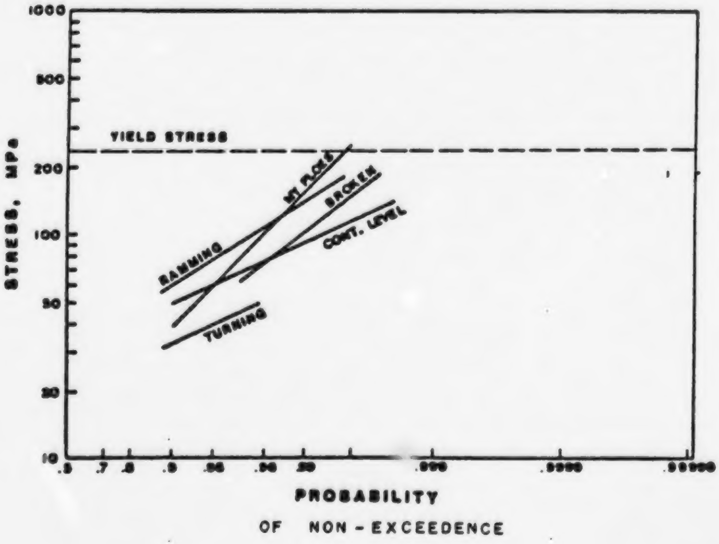
TYPE 2 DISTRIBUTION



EXTREME FRAME STRESS DISTRIBUTION

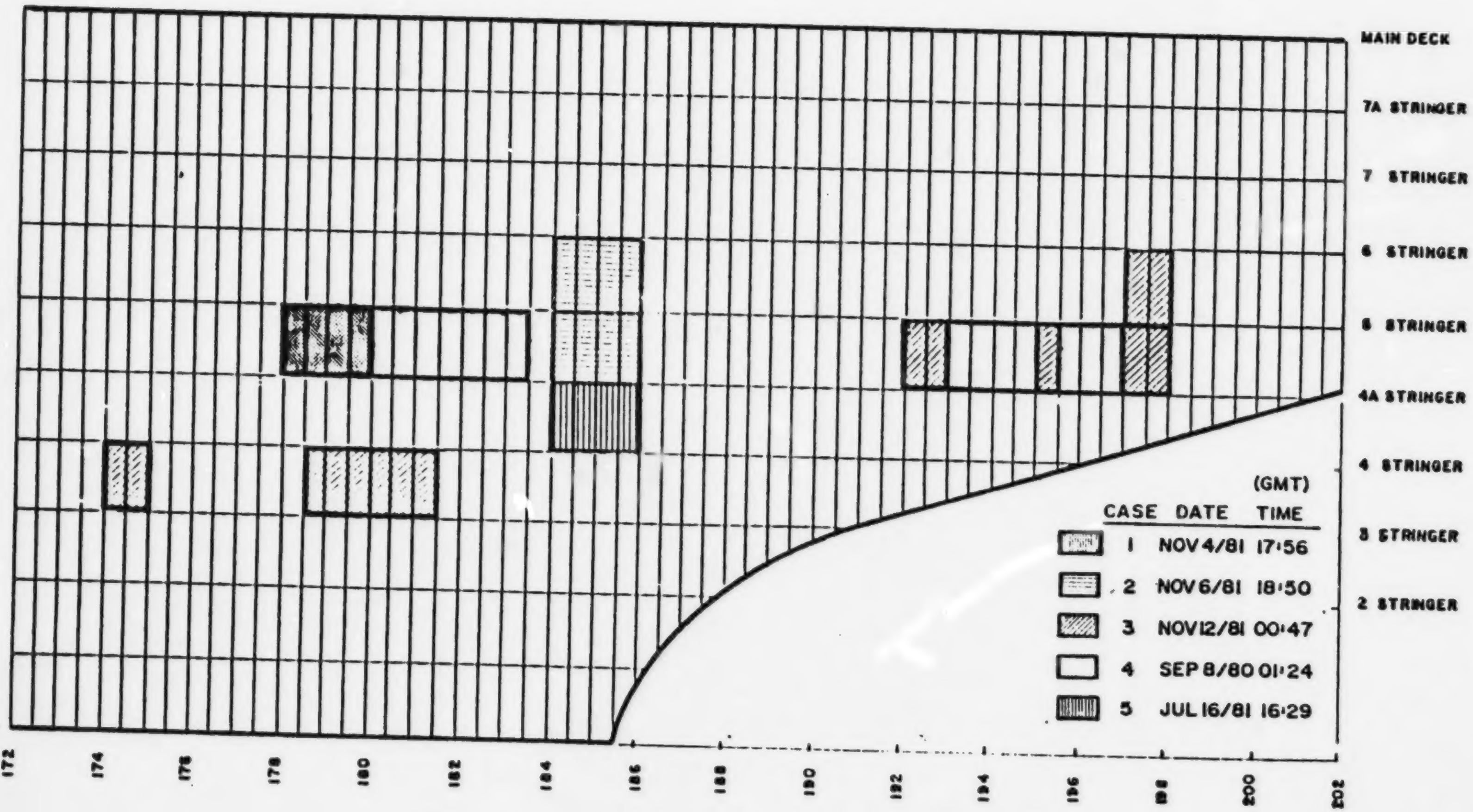
(Envelope of all frame data)

TYPE 2 DISTRIBUTION



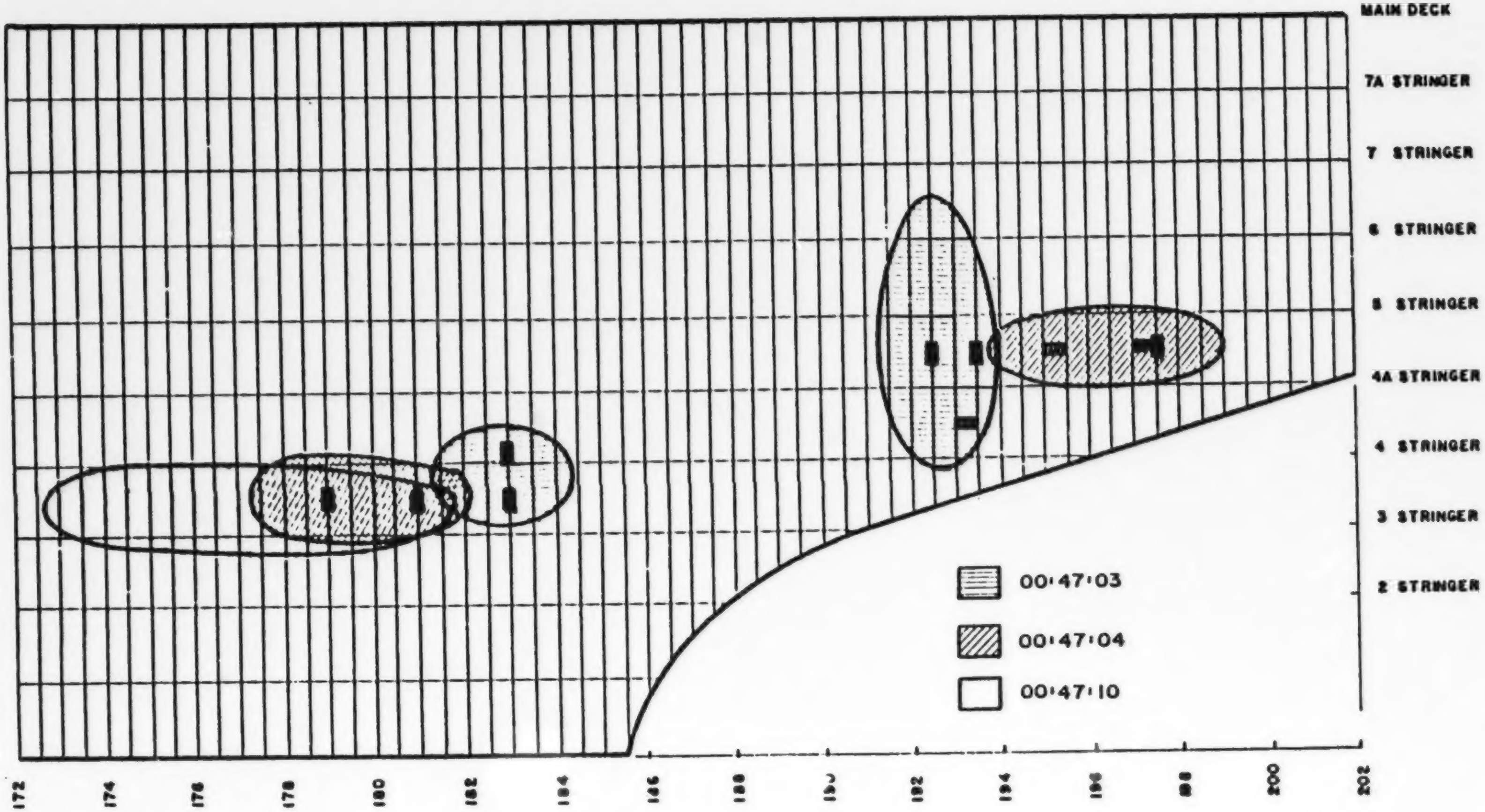
ATTACHMENT 5.10

AREAS of ICE ACTION on the BOW STRUCTURE DURING OBSERVED FAILURE CASES



ATTACHMENT 6.11

RECONSTRUCTED IMPACT CASE WITH A MULTI-YEAR FLOE



SECTION 7

INSTRUMENTATION SYSTEM

7.1 Introduction

In respect of the program objectives, as provided in Section 2, an instrumentation system was designed by German & Milne Inc., and installed aboard the MV. Arctic to monitor and record selected parameters with respect to structure, propulsion, steering, ship motions and relevant environmental conditions.

As a result of this activity, a significant database was acquired over three Arctic seasons and during four dedicated trial periods. Indeed, the database was so extensive that it offered an opportunity for analysis far exceeding the original program objectives. This led to two important results, namely:

1) a greater understanding was obtained of the various performance-in-ice characteristics of the MV. Arctic than was originally expected; and

2) an invaluable insight was gained into the principal requirements of future instrumentation systems to be used for more advanced research.

The analysts have worked with the database until no further useful information could be obtained and their evaluations invariably point out how specific modifications to the system could have provided much more useful data in their area of interest even though it may not have been part of the original objective. This type of evaluation is considered to be invaluable to those charged with developing the next generation of instrumentation system.

This report summarizes the evaluations made of the instrumentation system from the perspective of the system design and of the useful data obtained in light of subsequent analysis. The report is partitioned into sections. Following this introduction, the next section of the report gives a brief description of the system. This is followed by a section summarizing evaluations of the overall system and of elements of the system which provided data packages for specific analyses. The last section presents overall conclusions regarding the system.

7.2 System description

A general layout of the data acquisition system is given in Attachment 7.1 together with a block diagram in Attachment 7.2. The system was controlled by a Rolm 1063A mini-computer. The configuration of the system permits the use of 256 data channels of which 212 were originally used.

The system's capacity was approximately 1765 samples per sec. Seven sampling rates were available for individual sensors, ranging from 1 sample/10 sec. up to 1000 samples/sec. Available rates from any sensor must, of course, respect the total rate limitation of 1765 samples/sec. The sensor allocation was arranged into four groups as follows:

Groups	No. of sensors
Hull structure	169
Propulsion and steering	16
Ship motions	13
Environment	14
Total	212

Strain gauges accounted for the majority of the system sensors, 169 of the 212 original sensors. The balance consisted of accelerometers, gyros, temperature gauges, driven potentiometers and outputs from certain of the ship's instruments, e.g. Doppler Log. Other parameters such as visibility, cloud cover, ice cover and wind direction were recorded into the system manually.

Most of the strain gauges were located on the starboard bow area and originally, from frame 178 forward. Later this array was extended back to frame 168. The final strain gauge array for the starboard bow is shown in Attachment 7.3.

Strain gauge location analysis was performed by Fenco Consultants Ltd. and was based on the finite element method of structural analysis. Using this approach, the ice load and stress on the structure can be determined at any instant from the captured strain pattern. A full scale calibration of the structural response to known applied loads was performed to provide information for conversion of strain to load.

A closed circuit video system was included in the system to document environmental conditions. The data acquisition system was designed for automatic operation and to be run by personnel with a minimum of training.

7.3 System evaluation

The evaluation of the instrumentation system as installed on the MV. Arctic is discussed under the following two general headings:

Overall System Design - The design of the system itself, the hardware and software used, and the sampling strategies used to produce the database for analysis, and finally the operation of the system over the trial period; and

Database Appropriateness - The ability of the database to serve the researchers charged with analyzing the data. The analysis was broken in three main categories as follows:

- the evaluation of the ship's ice-transiting performance in the continous, ramming and manoeuvering modes of operation;
- the evaluation of the ship's propulsion system performance in the various modes of ice operation;
- the evaluation of the ship's hull structural performance in the various modes of ice operations.

7.3.1 Overall System Design

The database resulting from three years of operation of the instrumentation provides the means of addressing all the program objectives, particularly as they relate to the CASPPR provisions. The extent to which these objectives were met however, was dependent on the comprehensiveness of specific elements of the database in terms of:

- the reliability of the system components;
- the adequacy of the sample rates and patterns used in recording the data;
- the reliability of the database in terms of the data presented and the ability to relate that data to the calibration data;

- the availability of supporting logged data describing ship's operations of interest to the analyst on environmental conditions;
- the appropriateness of the data selected for recording in terms of the analysis anticipated for that data.

Reliability of Components

The computer and peripheral equipment performed well throughout but the failure rate of many of the hardware components, notable the strain gauges, was excessive. Effectively, in terms of total number of gauges, the complete array failed and was renewed during the 3½ year operating period. The strain gauge failures and those problems experienced in the signal conditioning cards, the master cards controlling the entry to the databus, and the closed circuit television could all be traced in a large part to the excesses of the environment in which the components were located. It would appear that words such as "waterproof" and "moisture resistant" have vastly different meanings when used to describe equipment normally used ashore when compared to a mariner's understanding of the terms. In spite of this serious shortfall, at the very heart of the system, the system was made to function and to support the task for which it was designed.

Adequacy of Sampling Rates

The capacity of the ROLM computer was limited to a total of 1765 samples/sec. from all 256 channels. This limitation imposed the need for a set of rates to be made available for each sensor which could be changed from time-to-time as the need arose to measure specific ship performance characteristics. The sampling rates imposed were adequate for most of the measurements, but analysis of certain dynamic responses of the structure and of the ship's motions could have benefited from the availability of sustained higher sampling rates. With current day computer technology, increased capacity to support higher sampling rates will not be a problem in the future.

Reliability of Database and Supporting Logs

The system did not incorporate a process for rigid documentation of calibration procedures, nor did it contain any reference channel for cross-checking channel group accuracy. Additionally, manual logs were not kept in an orderly manner with each operator using different techniques for recording vital environmental data and other ship operating events. It took a great deal of detective work on the part of the database analysts to identify which parts of the database were a true reflection of the measured parameter, and which parts of the written logs applied at the time.

Appropriateness of the Elements selected for Instrumentation for the subsequent Analysis

With the exception of an identified lack of parameters relating to the strength of the propulsion system, the elements of the ship selected for monitoring were well suited to the requirements of the subsequent analyses.

7.3.2 Database Appropriateness

It has been noted by all the analysts that the quality of the database improved with each successive season of system operation. This was particularly noticeable with certain propulsion, motion and environmental parameters which were common to all the various subjects of ship performance evaluation. Unfortunately for much of the test period, the sensors for some of these parameters were operating poorly or not at all. As a result, the first two years worth of voyage data contain very little that is useable for a reliable assessment of the ship's performance. The third year, plus tapes from the dedicated trials thus formed the basis for the analyses.

When the sensors were working properly, the sampling rates and patterns were adequate. Critical parameters, with the exception of the accelerations, were of good quality with little noise and good resolution. Accuracy was frequently in question however, as some sensors tended to drift off calibration. No method of verifying data integrity was included in the system and bad data encountered by the data reduction program frequently caused time consuming consequences. Additionally, the lack of more detailed logs of events and ice conditions limited the usefulness of some of the data. The data recording format, while non-standard, was not unreasonable or difficult to handle. Against this general background of the database, some specific comments follow in connection with the various subjects of analysis.

i) Ice-transiting performance

This embraces three components of evaluation, namely, continuous, ramming and manoeuvering modes of performance. The propulsion, motion and environmental parameters monitored for these purposes was adequate but, as noted above, the data gathered was sometimes insufficient or incomplete for an exhaustive analysis. Some specific comments follow:

Continuous-mode - Good results were obtained from this segment of the data analysis and the available parameters were considered to be adequate. Based mainly upon the dedicated trials, the ice conditions were reasonably well documented. The main problem related to ship speed where the Doppler Log became increasingly inaccurate as the speed dropped. Propeller pitch also needed re-calibration due to a zero shift.

Ramming-mode - The results obtained from this segment of the data analysis have provided a good understanding of the ramming process and were based entirely on the Admiralty Inlet trials.

Data acquired from the torque, propeller pitch, thrust and shaft RPM was found to have the quality and reliability necessary for ramming analysis. The recording of the ice conditions was generally not adequate and the selection of the fuel rack position to measure fuel rate produced erroneous results. The single most important parameter for ramming cycle analysis, ship's speed, from which distance, acceleration and resistance are derived was inadequate for the analysis.

The system took speed measurements from the ship's Doppler Log. The measuring range was set from 0 - 30 knots with sampling rates of either 1/10 samples/sec., or 1 sample/sec. The accuracy of the Log in the low speed ranges of interest to this study is poor. Additionally, the slow sampling rates set for the system presented problems in defining speed during the short pentration runs associated with ramming. The accuracy of the speed record when travelling astern was found to be completely unacceptable. Accordingly, a speed correction algorithm had to be employed based upon certain video records which were also of poor quality.

Manoeuvering-mode - A very limited analysis of the maoeuverability of the ship was effected from the data available. In general, the sensors were well suited to the measurements they were intended to make. When the sensors were functioning, and the system well calibrated, data, with the exception of low speed data from the Doppler Log, was reliable. Rudder torque based upon rudder stock strain gauges and hydraulic ram differential pressure proved to be impossible to calibrate.

It should be noted that the original program objectives did not call for a manoeuverability investigation and, thus, a test plan was not envisaged. Consequently, the analysis conducted of the limited database relating to this area of investigation was a bonus to the program and was sufficient to produce a general evaluation of the ship's manoeuvering qualities.

ii) Propulsive Performance

The system design was found to be adequate to provide data to evaluate the performance of the propulsion system but not adequate to evaluate the strength of the propulsion components.

To analyse the performance of the propulsion system, the recorded parameters of torque, thrust, RPM, etc. taken from the instrumentation fitted to the propulsion machinery met most of the program objectives. Exception is taken with the conversion equations presented by the designers with respect to the sensors measuring rudder differential pressure, propeller pitch angle, fuel rack position and vertical acceleration. These equations required modification to provide correct readings for rudder turning direction, propeller pitch, fuel flow and vertical acceleration, respectively. The malfunction of the RPM sensor during the first two seasons also limited the quantity of data available for performance and analysis.

The non-standard data format was found to be time-consuming to deal with. Additionally, the calibration strategies used for the system were not adequately documented and the system had no built in calibration check facilities. A serious lack of objective and reliable environmental data was also noted.

iii) Structural Performance

The noted improvement in the quality of the database with each successive season is most apparent in that part which relates to structure. This is to be expected as the portion of the instrumentation system relating to structure accounted for about 80% of the system and, as malfunctions were diagnosed and remedied, the benefits of these actions were reflected in the database.

The general location of the sensors was good in that the areas of the ship subject to the most ice impact activity was covered. However, the selection of grid sizes (0.2 m^2 to 1 m^2) for the sensors was considered, in some cases, to be too large for the expected impact areas. With a smaller grid size (no greater than 0.2 m^2) the load/strain algorithms would produce more precise pressure distribution information. The sensor array was modified during the second season of operation, extending the coverage aft from frame 178 to frame 168 to embrace the shoulder area but this was not accompanied by any change in the grid pattern. Despite these limitations, the database obtained from the principal sensor array on the starboard bow has produced good quantitative measures of the structural loads, pressures and stresses resulting from ship/ice interactions.

The secondary arrays established on the port bow and midships were of little value. This was partly due to less attention given to sensor maintenance but more importantly was due to the difficulty of making reliable load/strain interpretations from the large grid size adopted. The thermistors installed for hull temperature monitoring went out of action in the first season and gave no useful information.

Certain shortfalls in system operations were highlighted by the process of structural data analysis. The lack of consistent and comprehensive written logs to supplement the tape records and the various inconsistancies in the tapes themselves due to different operator techniques all conspired to make the task of analysis more challenging

7.4 Summary of findings

The instrumentation system installed aboard the MV. Arctic has been successful in addressing all the original objectives of the program. It is noted, however, that the acquired database has been used for more searching purposes than was originally intended and this process has brought into sharp focus certain fundamentals of importance to future systems, as follows,

- A clear definition of the vessel's qualities to be examined and the characteristics that are indicative of these qualities must be prepared prior to the design of the system. This may require some advance analytical or empirical research.

- A comprehensive program of analysis is also required prior to system design to ensure that the system and its operation are adequate to the needs of analysis. This in turn demands that an operational plan be developed and followed so as to ensure that the acquired database contains the right combination of parameters recorded at adequate sampling rates, etc., appropriate to the objectives of the analysis.

- All hardware should be suitable for a marine environment and installed with appropriate precautions to ensure adequate life expectancy. This is found to be a particular problem with strain gauges.

- An adequate fail-safe capability should be incorporated into the system to cater to the needs for redundancy in critical measurements relating to ship and ice parameters without which all other data becomes useless. The system should also incorporate a reference signal capability to test periodically the reasonableness of the data being recorded from various classes of sensors.

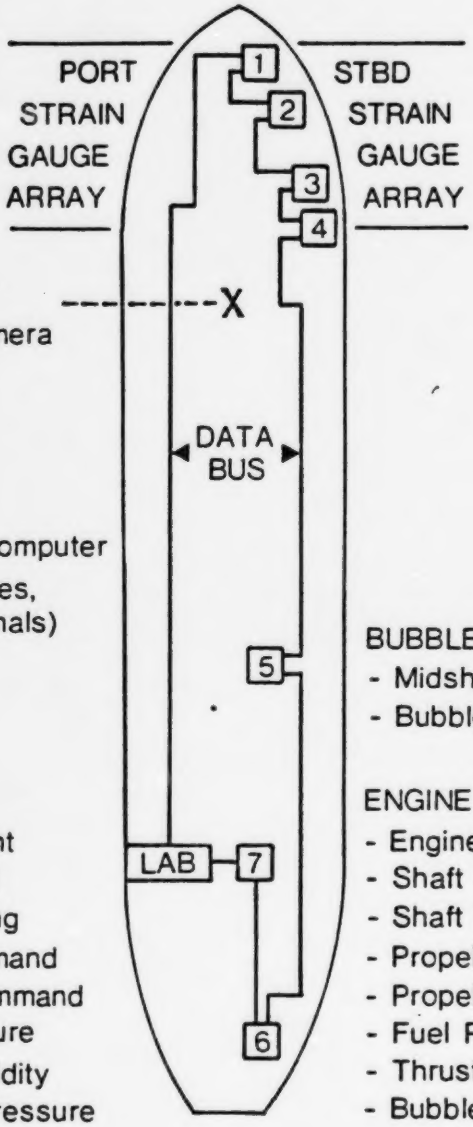
- A particular deficiency of the system was related to the low speed inaccuracy of the ship's hydracoustic Doppler Log. Supplementary or alternative methods of measuring low speeds ahead and astern are required which could include a different form of doppler and a fixed view video camera to track ice surface features.

- A careful manual log must be kept. Vital information which cannot be collected automatically should be input as part of a mandatory interactive logging procedure so that it can be included in the data file. Equipment operators should keep a system log on each channel noting calibrations, repairs, etc., and have available a record of the standard ship's instrument readings in a form which can be related to the test data.

In the overall, there is strong evidence to support the belief that all phases of a system (design, installation, calibration, operation, maintenance and analysis) should be performed by a single rather than by multiple organizations. In terms of end results, a single line of responsibility is much to be preferred.

ATTACHMENT 7.1

LAYOUT DIAGRAM OF DATA ACQUISITION SYSTEM



FORE PEAK (1 to 4)
- Hull Stress
- Hull Temperature
- Fwd Hull Accelerations

MAIN MAST
- CCTV Camera

LABORATORY
- Rolm 1603 Minicomputer
- Peripherals (Tapes, Floppys, Terminals)
- Main Interface
- CCTV Monitor

BUBBLER COMPT. (5)
- Midship Hull Stress
- Bubbler Manifold Pressure

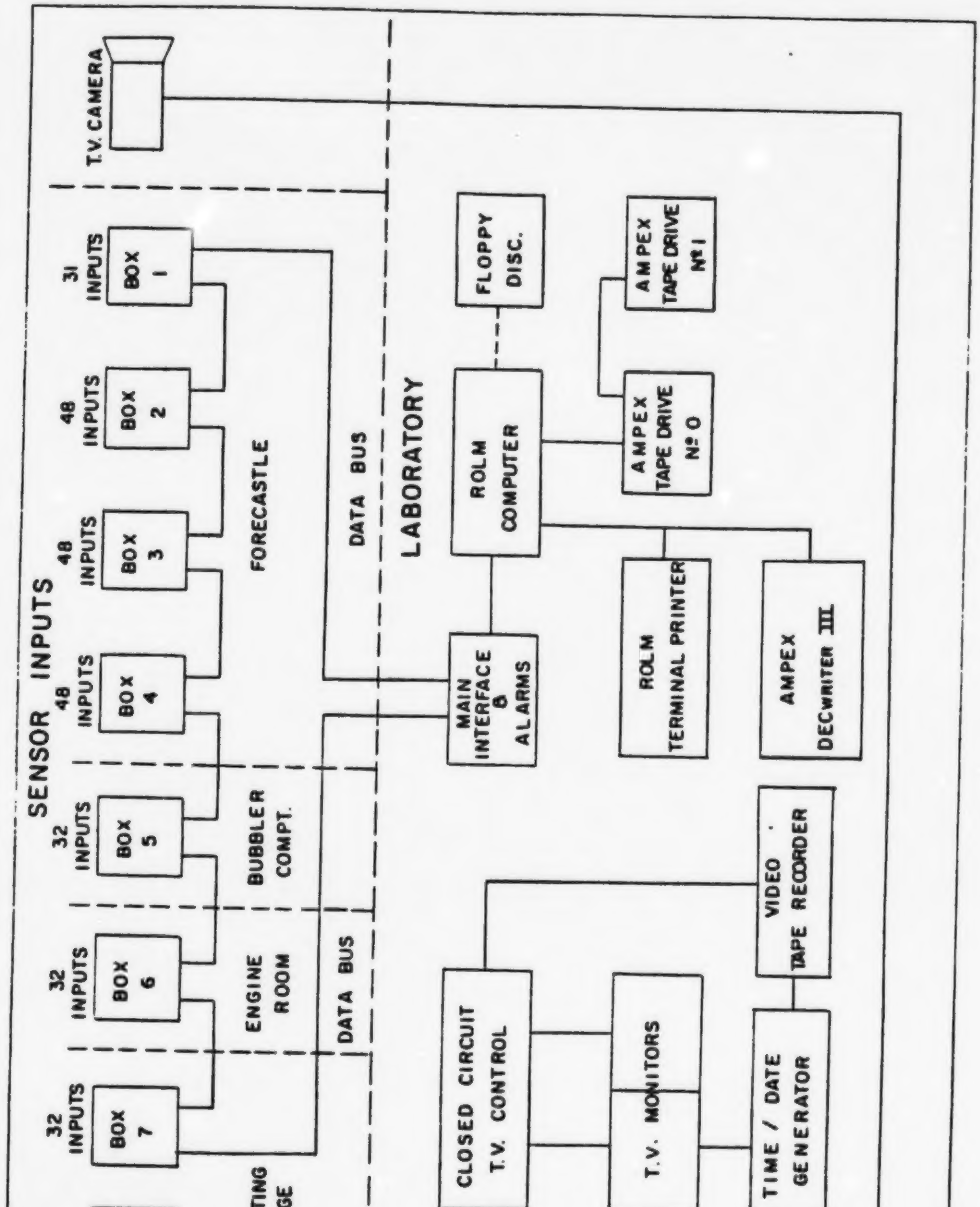
BRIDGE (7)
- Ship's Draught
- Ship's Speed
- Ship's Heading
- Rudder Command
- Propellor Command
- Air Temperature
- Relative Humidity
- Barometric Pressure
- Visibility
- Cloud Cover
- Ice Cover
- Wind Speed
- Wind Direction
- Pitch and Roll

ENGINE ROOM (6)
- Engine r.p.m.
- Shaft r.p.m.
- Shaft Torque
- Propellor Response
- Propellor Differential Pressure
- Fuel Rack
- Thrust
- Bubbler Valve Position
- Rudder Response
- Rudder Differential Pressure
- Aft Hull Accelerations

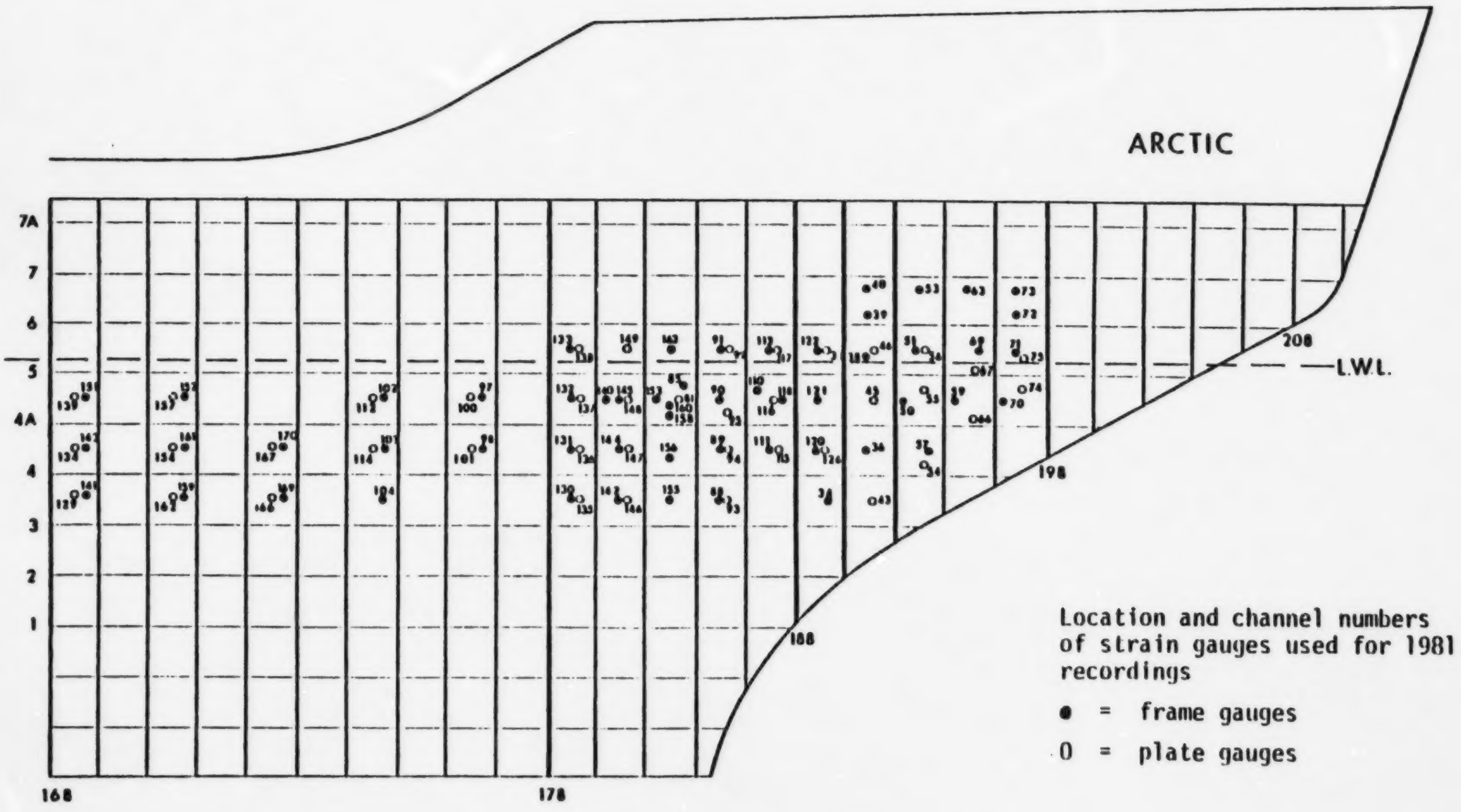
NOTE — Junction box numbers in parentheses

ATTACHMENT 7.2

BLOCK DIAGRAM OF THE DATA COLLECTION SYSTEM.



STARBOARD BOW ARRAY



Location and channel numbers of strain gauges used for 1981 recordings

● = frame gauges

0 = plate gauges

SECTION 8

FOCUS FOR FUTURE RESEARCH

8.1 Introduction

The findings contained in the various sections of this report will make worthwhile contributions to the fund of knowledge concerning the requirements and capabilities of arctic class cargo vessels. It can not be expected, however, that this single program of scientific research could be exhaustive in the sense of providing complete answers to all matters of technological importance for icebreaking cargo ship design and performance. A productive focus for on-going research would be to strengthen these findings and fill the gaps revealed by the present analyses. Accordingly, the following thrusts of research are advised for the appropriate areas of ship performance.

8.2 Ice-transiting research

1. Present continuous-mode predictive formulations are highly ship-specific and, at best, fall into two hullform groups based upon length/beam (L/B) ratios. One group relates to low L/B ratio vessels which includes dedicated government icebreakers, whilst the second group relates to high L/B ratio vessels which includes ice-capable cargo ships such as the MV. Arctic. A well-structured program of model-scale and full-scale research is required to unravel the complexities of icebreaking resistance prediction within each group and to bridge the gap between the two groups. Such a program should seek quantitative bases for the prediction of resistance due to the following hullform variables:

   - principal dimensions, dimensional ratios and overall form coefficients;

   - bow geometry relative to stem, entrance and flare angles;

   - parallel midbody flare and stern configurations.

The program should start from a basis of level homogeneous ice resistance taking account of appropriate ice-related variables including thickness, strength (flexural, crushing and modular) and hull/ice friction. Further variables may then be added including snow cover, ice pressure and ridging where the objective of the latter is to determine the "significant" ridge which the hullform could breach without stopping under specified approach conditions.

2. Present ramming-mode predictive methods are much less advanced than for the continuous-mode and would provide a further area of research complementary to the above. The main objective is to maximise the advantage of the transition zone between the two modes and, accordingly, considerations of bow geometry would be incomplete without appropriate ramming research. An integral part of such a program would be to develop an analytical model for the satisfactory classification of ridges.

3. The present investigations of the ramming-mode capabilities of the MV. Arctic have identified an optimum ramming strategy for the vessel. A ship-handling program should be put into effect to test and to confirm the strategy and, ultimately, to convert it to a semi- or fully-automated ship control system.

4. A program of model- and full-scale tests should be put into effect to develop the criteria and standards needed for good directional stability and manoeuvering qualities of icebreaking ships. Such a program should include the investigative research necessary to develop standards for rudder size and strength, directional and turning criteria for these vessels. The program should also clarify the indication of improved manoeuverability obtained on the MV. Arctic by the use of heel and the bubbler.

8.3 Propulsive research

1. The present findings have provided evidence of the operational and cost effectiveness of the MV. Arctic, propulsion system. A comparative investigation should be performed to evaluate the relative merits

of this system and other icebreaker propulsion systems with a view to integrating the best combined features in any particular application.

2. The instrumentation system fitted on the MV. Arctic propulsion plant was not designed to collect data from which complete conclusions could be made with respect to propulsion system strength. In particular, gear tooth stresses, shaft bending, sterntube bearing and thrust block vibrations could not be measured nor also propeller blade and spindle stresses. A further program is advised which would address these supplementary investigations to augment the present evaluations.

8.4 Structural research

1. The present findings have identified the relative magnitudes of loads and pressures carried by the structural members of the bow of the MV. Arctic under various ice-transiting conditions. These findings should be amplified by a supplementary program to obtain more precise information on the relationships of pressure to area of ice contact, ice thickness, and ship speed. Such a program could be incorporated into the second generation instrumentation system being fitted to the MV. Arctic.

2. A program to investigate the structural fatigue characteristics of icebreaking vessels should be initiated. This program should aim to establish stress/frequency damage relationships for the structural members in various ice-transiting environments, taking temperature effects into account. The ultimate aim would be to evaluate the potential for using fatigue as the basis for hull inspections.

3. The double skin construction used for appropriate icebreaking vessels comprises an extensive matrix of webs, frames and stringers sandwiched between the outer and inner plating in a space as little as three feet wide. This arrangement should be evaluated from a ship construction view point which best couples the strength design requirements with ease of fabrication.

8.5 Ice-related research

The above programs of research are aimed at improving the ice-capable design of arctic vessels. Full advantage can only be taken of such additional technological knowledge, however, if there is a corresponding advancement in the knowledge of the ice regimes in which such vessels will operate. To that end, a program to define more precisely the extent and the frequency of the ice conditions occuring in the CASPPR zones and seasons would assist the regulator, designer, constructor and operator to optimize the creation and serviceability of these vessels.